DREDGED MATERIAL RESEARCH PROGRAM

CONTRACT REPORT D-76-3

STATE-OF-THE-ART SURVEY AND EVALUATION OF OPEN-WATER DREDGED MATERIAL PLACEMENT METHODOLOGY

by

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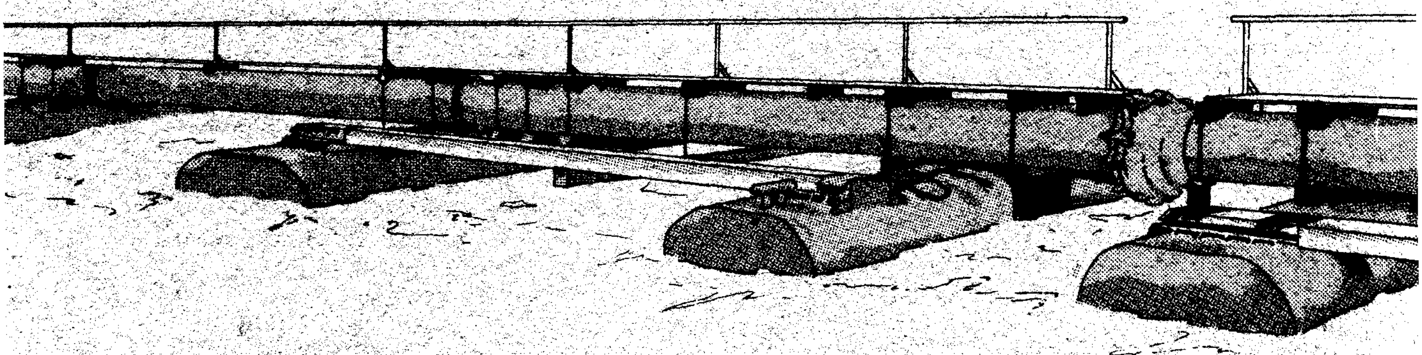

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SUBJECT: Transmittal of Contract Report D-76-3

TO: All Report Recipients

1. The Contract Report transmitted herewith represents the results of one of two research efforts completed as part of Task 3A (Aquatic Disposal Concepts Development) which was originally part of the Productive Uses Project of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 3A was transferred in July 1975 to the Environmental Impacts and Criteria Development Project which is concerned with the environmental effects of open-water disposal of dredged material, as well as the spatial and temporal distributions of dredged material discharged into various hydrologic regimes.

2. The research was conducted as Work Unit 3A02 to investigate new open-water disposal concepts for dredged material. Specific objectives were to study the feasibility of accurately placing dredged material in subaqueous borrow pits and to develop new concepts to improve open-water disposal of the large volumes of fine-grained material from maintenance dredging of industrial harbors.

3. The investigation reported herein addressed itself to identifying and evaluating those factors affecting open-water disposal of dredged material and documented three primary types: the disposal environment, the equipment, and the equipment operation. When dumped the dredged material cloud passes through four phases: descent, collapse, deposition, and erosion and resuspension of sediments. The variables which readily affect these disposal processes include water depth, bulk density of the slurry, the spreading rate of the material, dump volume, initial descent velocity, impact velocity, and the currents.

4. Barges, scows, and seagoing hopper dredges can be used in the disposal of dredged material into subaqueous borrow pits if the vessel is able to transport an adequate volume of material, navigate with precision, position itself relative to the pit, and maintain position during disposal.

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5. Several alternative concepts to improve ocean dumping procedures were considered to extend the limits of feasibility of borrow pit disposal. The primary concept discussed involved modification of the hopper dredge to allow pump-down of the dredged material back through the draghead into the borrow pit. Similar modifications were discussed for barges and scows, as well as techniques to alter the physical characteristics of the dredged material to minimize dispersion and subsequent erosion.

6. The study concluded that considerable research needs to be undertaken in the field of open-water disposal investigating the sediment physics, the effect of different dredging techniques, and the importance of water content, compaction, cohesive strength, and flocculation. These recommendations are being used to guide the planning of research within Task 1A and Task 1B.

G. H. HILT
Colonel, Corps of Engineers
Director

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The dumping of dredged material into a borrow pit is feasible using hopper dredges provided that an auxiliary navigation capability is available such as an instrumented buoy at the center of the borrow pit or an electronic precision navigation system. Borrow pit dumping is less easily undertaken with barges and tug boats because of the inability to accurately control the position of the barges.

Borrow pits must be several acres in size and have dimensions sufficient

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20. ABSTRACT (Continued).

to allow radial spreading of several hundred feet. Very little field data is available to establish the actual depositional dimensions of discrete disposal operations. Mathematical models simulating the disposal event have not been verified but appear to adequately simulate the phenomena observed in the few field research efforts undertaken.

Estimates of the long-term fate of dredged material placed in a borrow pit cannot be made at the present time. If the material is cohesive, borrow pit sites should be selected that have bottom current velocities of 0.1 ft/sec or less and the dumping operation should be done at a time of year to allow several months for stabilization to occur prior to the winter storm season.

Polluted dredged material can be covered over with sand within a borrow pit by a modified hopper dredge at a cost of approximately $2500/acre. The time of the covering process would be dependent on the polluted sediment type. If the material were fine-grained, a period of time would have to be allotted for stabilization so that it could support the weight of the cover material. However, the covering concept is not considered an efficient means of preventing pollutant removal and resuspension unless it can be undertaken immediately after disposal.

Field and laboratory studies should be initiated to identify and quantify the physical mechanisms associated with open-water disposal operations. The field studies should be undertaken at typical disposal sites and should evaluate different sediment types and compare potential erosion and resuspension rates. The effects of different dredging techniques need to be investigated to determine the importance of water content, composition, cohesive strength, and flocculation. A field demonstration and evaluation of the horizontal pumpdown concept should be developed.

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PREFACE

The study reported herein, "State-of-the-Art Survey and Evaluation of Open-Water Dredged Material Placement Methodology," was conducted by JBF Scientific Corporation, Burlington, Massachusetts, during the period May 1974 to February 1975. It was sponsored by the U. S. Army Engineer Waterways Experiment Station (WES), Environmental Effects Laboratory (EEL), under the Civil Works Research Program, Dredged Material Research Program (DMRP). The study was prepared under Contract No. DACW39-74-C-0087.

Messrs. Edward E. Johanson, Stuart P. Bowen, and George Henry conducted the study for JBF Scientific Corporation and prepared this report. Dr. Roger T. Saucier, Special Assistant for the DMRP, was the Contracting Officer Representative. Technical discussions and contributions were also made by Mr. Barry Holliday of WES. The study was under the general supervision of Dr. John Harrison, Chief, EEL. The Director of WES during the period of this contract was COL G. H. Hilt. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
miles (U. S. nautical)	1.852	kilometres
square feet	0.09290304	square metres
cubic yards	0.7645549	cubic metres
acres	4046.856	square metres
feet per second	0.3048	metres per second
cubic yards per hour	0.7645549	cubic metres per hour
gallons (U. S. liquid) per minute	3.785412	cubic decimetres per hour
pounds (mass)	0.4535924	kilograms
tons (2000 lb, mass)	907.1847	kilograms
fathoms	1.8288	metres
gallons	3.785412	cubic decimetres
knots (international)	0.5144444	metres per second
feet per minute	0.3048	metres per minute
miles (U. S. statute) per hour	1.609344	kilometres per hour

PART I: INTRODUCTION

1. Each year large quantities of dredged material are disposed of by dumping in open water. Some of this material is potentially polluted sediment from maintenance dredging of industrialized harbors, and there is reason to believe that precision, or controlled, placement of this material on the ocean bottom with or without the confinement afforded by natural or man-made depressions will mitigate or avoid significant adverse effects.

2. This study was directed to establishing the feasibility of controlled placement of dredged materials in open water, with special emphasis on the ability to use subaqueous borrow pits as receptors for the dredged material. The study involved the feasibility of finding the pit, positioning a hopper dredge or barge over the pit, holding position during the dumping operation, and determining whether the material would stay in the pit after it was dumped. While the study emphasized borrow pit placement of dredged material, it was conducted in a manner to address the broader aspect of precision placement of material on the ocean bottom whether a pit was available or not.

3. Pits most commonly are formed by sand and gravel mining operations. The size and shape of pits, both in this country and abroad, were established to use as an input to the feasibility analysis. Navigation capability was examined for dredges and tugboats as presently configured, as well as with enhanced capability that can presently be implemented. Special emphasis was placed on the status and capability of Loran C. Dredge and barge operational considerations were examined to establish the capability to maneuver and hold position over a borrow pit.

4. The most difficult task was to establish the short-term and long-term fate and behavior of the material once it left the dump vessel. Mathematical models exist to predict the short-term behavior, but they have not been field verified. An approach was adopted whereby

available field data and field observations were used to estimate the behavior of the material; predictions were then made using the two most realistic models; and these predictions were compared to the field data.

5. Extensive investigation of the most comprehensive model was conducted including a sensitivity analysis. Predictions and field observations yielded the same general conclusions and enabled the feasibility of hitting the pit to be assessed. Uncertainty exists both in the precise dimensions of the material as it settles on the bottom and in its ultimate fate especially with regard to resuspension and erosion.

6. An investigation was also conducted to establish improved placement methodology. An innovative way to reduce, or eliminate, dispersion is described. The technique is based on using hopper dredges to pump the material to the bottom while transiting at a controlled speed, thus eliminating the horizontal velocity at the pipe discharge point and reducing dispersion. The feasibility of placing a clean cover (sand) over a borrow pit after it is filled was also examined.

7. In the following sections the factors relevant to precision open-water placement of dredged material are identified and evaluated. Mathematical models for predicting dispersion are examined and the results of a sensitivity analysis are presented. It is concluded that borrow pit dumping with hopper dredges is feasible and, under ideal conditions, precision dumping from barges may be possible. Uncertainties in the relevant factors are clearly identified and recommendations are made for resolving these uncertainties.

PART II: FACTORS AFFECTING OPEN-WATER PLACEMENT

8. The factors affecting open-water placement of dredged material, with special emphasis on borrow pits, have been identified and evaluated. These factors are presented in this chapter under the broad categories of

- Disposal Environment
- Operational Considerations
- Disposal Equipment

The relevant factors were examined in a manner that would allow general, rather than specific, conclusions. The material presented herein is applied in Part III to establish the feasibility of open-water placement.

Disposal Environment

Subaqueous borrow pits

9. Subaqueous borrow pits are the holes that remain on the floor of a water body after a mining operation has been completed. Borrow pits are generated as a result of sand and gravel mining, shell dredging, and beach replenishment or nourishment. However, the borrow pits of interest in this study are those located offshore and further seaward than those normally generated by beach replenishment projects. The purpose of filling these holes with dredged material is to reduce the availability of polluted sediments to the ecosystem. Since the nearshore high-energy ocean or estuary bottom presents too great a likelihood of subsequent resuspension and dispersion of the sediments, offshore pits in deeper water offer greater protection against erosion of the deposit.

10. Marine sand and gravel mining in the United States is in the early developmental stages. Presently available resources of sand and gravel in the coastal states will be depleted by approximately the year 1988.[1] Urban expansion and restrictive zoning limit the possibility of acquiring new reserves. Since sand and gravel have a relatively low value compared to costs for shipping, the economic limit on distance of haul is only about 50 miles.[1] Marine sand and gravel

deposits appear very attractive to the sand mining industry since large deposits are located near major metropolitan areas and the cost of barge transportation is relatively low.

11. While little marine sand and gravel mining has been done in this country, in the United Kingdom it is estimated that 13 to 15 percent of construction aggregate currently comes from offshore sources and that within 10 to 15 years all production will come from the sea. According to Hess,[2] there are at least four metropolitan areas (Boston, New York, Los Angeles, and San Francisco) where industry has shown substantial interest in offshore deposits. Since the value of all sand and gravel mined in the United States is approximately $1 billion/yr and the demand for sand and gravel is expected to triple or quadruple by the year 2000, there will be considerable pressure to use offshore deposits. If environmental problems can be overcome, in the near future the offshore sand and gravel mining industry will undoubtedly become very active.

12. The feasibility of filling offshore borrow pits with dredged material will depend in part on borrow pit location (distance from shore) and configuration (size, shape, side-slope angle). Few offshore pits exist in the U.S. at this time; a survey by Broughton* revealed less than 25 pits in the coastal waters of the United States. Of these, the shallowest water depth (to pit bottom) is about 20 ft and the deepest about 75 ft. An average value is considered to be 45 ft. Pit depths are generally 2 to 20 ft. The holes range in area from 0.5×10^6 to 1.5×10^6 sq ft and tend to be circular or rectangular rather than long and narrow.

13. Thompson[3] has suggested that environmental considerations may have a significant influence on borrow pit geometry. Limited excavation over extensive areas would allow a layer of sand to remain and thus would cause less harm than deep pits on the ocean floor covering a limited area. Deep borrow pits might interfere with fishing

*Personal Communication, July 1975, Gerald D. Broughton, Engineering Geology and Rock Mechanics Division, Waterways Experiment Station.

trawlers and harm bottom-dwelling communities. A limited pit would safeguard against opening a different bottom interface through removal of all sand. The limited pit would also provide a better fish habitat.

14. The type of dredge will also affect the geometry of the borrow pits. Sand and gravel mining hopper dredges, such as are common in the United Kingdom, produce relatively shallow pits. Hydraulic suction dredges are capable of mining a deposit in greater depth and typically produce deeper pits with steeper side slopes.

15. Experience with offshore sand and gravel mining in the United Kingdom shows that prefered water depths are 30 to 40 ft, but where the extent, quality, and location of the site warrant dredging, water depths up to 120 ft are not a serious obstacle.[4] Water depth is important since, at depths greater than about 100 ft, the conventional suction pump is not considered efficient and either jet-assisted suction pumps or pure jet pumps must be used. As nearshore deposits become exhausted, deeper deposits will be used. While more sophisticated pumping systems would allow mining at almost any depth, shallow deposits will be used first. In the near future, water depth will probably be limited to about 100 ft.

16. Few direct measurements of subaqueous borrow pit side-slope angles have been made. Hess[4] states that measurements of sand pits dredged in the Netherlands show slopes ranging from 1:10 to 1:20 (about 5-1/2 to 2-1/2 deg). Observations of sand waves indicate typical slopes of 1:8 (about 7 deg), but on portions of the waves, slopes as steep as 1:3 (about 18 deg) have been observed. Borrow pit slope stability varies considerably from one area to another depending on deposit characteristics and current conditions. The major sediment character factors influencing slope are grain size, its distribution and uniformity, degree of compaction, and sediment permeability and pore pressure.[4] In general, it does not appear that pit side slopes will be effective in limiting the spread of dredged material during the density-flow stage unless unusually

steep slopes can be produced either during the mining operation or prior to filling with dredged material.

17. Distance of borrow pits from shore depends in part on the dredge operator's evaluation of the quality of potential dredging sites, distance from markets, and difficulty of dredging at the site due to weather conditions, water depth, currents, etc. An additional constraint is that permits for dredging are generally required. In the United Kingdom, concern over coastal erosion has caused new permits to be generally granted only for operations outside the 3-mile limit.[4] Typical distances of borrow pits from shore in this country range from 15 to 20 miles with a maximum of 50 miles. Nearshore sand deposits are controlled by State government and deposits outside the 3-mile zone are controlled by the Federal Government.

18. Water circulation and mixing are important factors affecting the placement of dredged material in borrow pits. Stratified, stagnant conditions tend to minimize initial spreading of the dumped material and reduce subsequent erosion, particularly during the first few days after dumping while the deposit is consolidating. However, stratification may create anoxic conditions and high concentrations of toxic hydrogen sulfide within the borrow pit.[5] Pratt et al.[6] have suggested an important factor in minimizing erosion and dispersion of dredged material deposits: colonization of the material by benthic animals stabilizes the surface both by production of fecal pellets and by cementing agents generated by tube-dwelling polychaetes. If environmental conditions are so poor that these animals cannot become established, the deposit will probably be more susceptible to resuspension and erosion.

19. Flow conditions in dredge holes have been discussed by Polis,[7] who has reviewed the literature concerning the ecological effects of borrow pits. He found that density stratification may occur in borrow pits due to intrusion of more saline water or thermocline formation; however, wind mixing and tidal currents tend to destroy this stratification. Borrow pits with large horizontal dimensions

compared to depth are less likely to become stagnant because ambient currents can more easily mix with pit water. Since future sand and gravel borrow pits will be many acres in size and perhaps at most be 10 to 20 ft deep, it is reasonable to assume that stagnation will not be a problem and that the geometry of the borrow pit will not appreciably affect near bottom currents.

Dredged material characteristics

20. Dredged material may consist of any substances which exist in the sediments at the bottom of waterways. The major components will be solid inorganic particles ranging in size from molecular dimensions up to large rocks and boulders, an organic fraction, and water. Additionally, relatively minor amounts of pollutants (heavy metals, pesticides, algal nutrients, oil and grease, etc.) will be present. When considering dredged material in a general sense, it is difficult to characterize the range of composition in a useful way, but a number of practical generalizations are possible, particularly in view of the specific requirement of placing dredged material in borrow pits.

21. The most important factors affecting dredged material placement, and the subsequent potential for erosion and resuspension, will be the size distribution of the particles and the bulk density of the dredged material. Size will affect both the particle settling rate and the degree of cohesion among particles. Bulk density will determine the rate of descent immediately following the dump and is a function of the density of individual particles, the water content, and the proportion of lighter materials such as organics. The presence of trace pollutants will have very little effect on settling and dispersion.

22. Soil or sediment particles are usually grouped by size into four categories[8] as shown below.

Gravel	2.0 mm to 152.4 mm
Sand	0.06 mm to 2.0 mm
Silt	0.002 mm to 0.06 mm
Clay	<0.002 mm

23. The division between sand and gravel is arbitrary and is not related to changes in properties. Silt differs from sand by tending to

become fluid as the moisture content is increased. The distinguishing feature of clay is its cohesive strength, which increases with a decrease in moisture content. Clay properties are influenced not only by particle size and shape, but also by the mineral composition.

24. Consideration of methods of dredging and the nature of the sediment being dredged will lead to generalizations concerning the sediment that might be placed in borrow pits. Dredging may be accomplished by hydraulic suction dredge, bucket dredge, or hopper dredge. Hydraulic suction dredges are limited to sediments that are either fluid or can be made fluid by the cutterhead. The most common disposal method for hydraulic pipeline dredged material is discharge through a pipeline to a disposal site at the edge of the channel or into nearby diked disposal area. Since the borrow pits of interest will exist some distance offshore, direct pumping to the site will not generally be possible. If a hydraulic dredge were to be used in conjunction with borrow pit disposal, the dredge could fill barges that would then be towed to the site by tugs. During transport some settling out of the larger particles and consolidation of materials in the barge could be expected. This process would also take place in a hopper dredge. At this time the extent of these effects and their impact on the dumping operation, particularly the dispersion process, is unknown.

25. Bucket dredges may also see use in dredging sediment for placement in borrow pits, but several factors indicate that bucket dredges would find limited application. First, operation of bucket dredges is more expensive than either of the other two types, and so find use primarily when excavation conditions are difficult, such as due to large rocks, and in cases where close control is required, such as around docks and other obstructions. The number of bucket dredging operations will therefore be limited. Perhaps a more important factor acting to minimize bucket dredging is that the sediments to be placed in borrow pits are presumably highly polluted or else the added expense of placement in the distant pit could not be justified. In most cases a highly polluted sediment will be

relatively fluid in nature due to its high concentration of fine-grained material. Bucket dredges are ineffective in excavating fluid sediment and so will not be suitable for these jobs.

26. The hopper dredge will be most effective for borrow pit operations. A factor closely related to the type of material collected in the hoppers will be whether overflowing will be allowed. If the hoppers are used essentially as settling tanks so that the coarser particles settle out and finer materials are discharged back into the dredging area, then the water content of the hopper load will be low compared to a situation where no overflow is allowed. Again, since borrow pit filling will presumably be used for polluted sediments, it is likely that overflowing will not be permitted to occur and therefore the load will consist of material with a high water content. This method is presently being used in dredging of the Delaware River and indications are that the load consists of 25 to 40 percent solids. The effect of changes in the operation of dredges on the physical characteristics of the dredged material is being investigated by the San Francisco District of the Corps of Engineers and the results, which should be available late in 1975, will allow better characterization of materials dumped from hopper dredges.

27. Based on these factors the following general statements can be made concerning sediment to be placed in borrow pits.

- a. The sediment will most probably be classified as polluted if dredged from a harbor with industrial activity.
- b. Particle size will be predominantly in the clay and silt size ranges.
- c. Water content will be high due to the methods of dredging and the inability to allow overflow of the collecting barge or hopper.
- d. For the purposes of borrow pit dumping, the important dredged material characteristics are particle size and bulk density. Cohesive effects may also be important, but no data are presently available on this parameter.

Transport mechanisms

28. In assessing the ability to place dredged material in subaqueous borrow pits, it is important to have a conceptual understanding of how dredged material behaves when dumped into the ocean. As presented by Clark et al.,[9] the total transport can be divided into four basic transport phases:

- a. Convective descent
- b. Collapse
- c. Long term dispersion
- d. Bottom transport and resuspension

The mechanics of the four transport phases will be discussed, followed by descriptions of mathematic dispersion models considered to have application to precision dumping of dredged material.

29. Convective descent. For this discussion dredged material is assumed to be dumped essentially instantaneously such as from a hopper dredge or a dump barge. Under these conditions the dumped material possesses an initial downward momentum and a density greater than that of the surrounding water. These result in forces that cause the material to settle in the form of a cloud, or density current, rather than as individual particles. As the cloud settles, shear stresses develop at the interface between the moving cloud and the ambient water. These stresses result in dissipation of the initial momentum and in the creation of turbulent eddies that entrain ambient fluid. In the case of clouds possessing an initial momentum, vortex rings will form at the time of release and will tend to cause deeper penetration of the ambient water.[10]

30. In terms of precision placement of dredged material, the most important aspect of this type of behavior is that it occurs very rapidly. Based on observations at the New Haven, Connecticut, dump site, Gordon[11] estimated the convective descent velocity for barge-dumped material to be 1 ft/sec in 60 ft of water. Marine silt having a high water content was dumped from a scow and measurements of cloud velocity were made with a transmissometer at known distances from the discharge point.

31. Observations, also by Gordon,[12] of another dump at the New Haven site again showed very rapid descent. In this case 2300 cu yd of dredged material contained 66 percent water, and the solid portion was 15 percent sand, 60 percent silt, and 25 percent clay. The water depth at the site was 51 ft, and the transmissometer was 6 to 7 ft off the bottom and 15 to 20 ft from the hull at the scow's midship. The time required for the scow to unload was 12.8 sec. From the opening of the scow doors to first observation of the turbidity cloud, the elapsed time was 18.6 sec. It is not known whether the transmissometer observation of the passage of the cloud occurred during the convective descent phase or after the cloud had impacted on the bottom with subsequent horizontal transport across the bottom. If it could be assumed that the cloud descended directly onto the transmissometer, then the descent velocity would be 2.4 ft/sec. However, if the transmissometer observation was of the spreading cloud after bottom contact, then the convective descent velocity would have to have been even greater.

32. The important point in the preceding paragraph is not the exact velocity of the cloud, but that instantaneous dumping of dredged materials in relatively shallow water produces a rapid convective descent of the material with a vertical velocity of at least 1 ft/sec and possibly much greater. Settling velocities calculated for individual particles do not apply during this form of transport. Since the time during which the cloud is in contact with the upper portions of the water column is a minute or less, ambient water currents, except near the bottom, are of little consequence in dredged material placement in borrow pits, except as they affect the transport of any turbidity cloud that may be generated during the descent. If near bottom currents are low, such as may occur below a pycnocline or in the shelter of a borrow pit, then precision dumping may proceed under almost any current condition occurring in the upper portions of the water column, except for turbidity cloud considerations.

33. Collapse. The second phase of transport occurs when the cloud begins a dynamic vertical collapse characterized by horizontal spreading. Collapse is driven primarily by a pressure force and resisted by inertial and frictional forces. Dynamic collapse will occur when the cloud encounters a boundary, either a pycnocline or the ocean bottom. In the case of precision dumping of dredged materials into borrow pits it is important that, if a pycnocline exists, the cloud will penetrate the layer and reach the ocean bottom.

34. An indication of whether penetration will occur is given by an expression developed by Sullivan and discussed by Brooks.[10] Based on dimensional analysis and small scale laboratory experiments Sullivan developed the following empirical equation:

$$\Lambda = \frac{(\rho_2 - \rho_1) Z^3}{(\rho_i - \rho_1) V} \tag{1}$$

where
- Λ = a dimensionless parameter
- ρ_2 = density of lower layer
- ρ_1 = density of upper layer
- Z = depth from release point of interface
- ρ_i = initial density of heavy fluid injected
- V = volume of heavy fluid injected

The following criteria were determined experimentally: if $\Lambda > 29$, less than 10 percent of the injected slug penetrates the lower layer; if $\Lambda < 1.5$, more than 90 percent of the injected slug continues into the lower layer. For a value of Λ between 1.5 and 29 penetration will be between 10 and 90 percent.

35. As an example, using the data for Gordon's dump conditions at the New Haven dump site and density data for a severe pycnocline, i.e., $\rho_2 = 1.030$; $\rho_1 = 1.023$; $Z = 40$ ft; $\rho_i = 1.51$; and $V = 62{,}100$ cu ft, then $\Lambda = 0.015$, indicating that the lower layer would be easily penetrated. If dumping were accomplished from a compartmented scow with one-tenth the volume (6210 cu ft), then Λ would

still be only 0. 15 and penetration would still occur. If the water depth to the interface were 100 ft and dump volume were 62, 100 cu ft, Λ would be 0.23 and penetration would occur. Similarly, if the water depth were 100 ft to the interface and the volume dumped were 6210 cu ft, then $\Lambda = 2.3$ and penetration would be incomplete.

36. Brooks cautions against complete acceptance of Sullivan's criteria because the experiments were conducted at a low Reynolds number for which the flow was partially laminar. However, several tentative conclusions can be drawn. First, for dredged material dumped in shallow water, penetration of a pycnocline is very likely. Second, if problems are to occur, they will probably happen in deeper water since the value of Λ increases as the third power of the interface depth. Third, to maximize the likelihood of interface penetration, the volume of material dumped should be maximized by using the newer split-hull barge rather than the older compartmented type. Fourth, a slow continuous release would result in less penetration than a sudden release.

37. In general, sudden releases of fairly large quantities of dredged material in shallow water will penetrate a density layer and impact on the ocean bottom. The cloud will flatten out and appear somewhat like a pancake as it assumes a horizontal circular shape (assuming a flat bottom and no obstructions) with a small vertical dimension. Under these conditions, flow will continue in the form of a density or turbidity current.

38. It is possible to interpret Gordon's observations at the New Haven dump site[11] in terms of a collapse phase. A transmissometer was held 3 ft above the bottom at a distance of 3 m from the scow. At that time the bottom current was 0.3 ft/sec. The time required for the dredged material cloud to fall through 55 ft of water, impact on the bottom, and spread laterally through 85 ft of water was 155 sec. Highly turbid water continued to flow past the transmissometer for 4.5 min, after which there was an irregular turbidity decrease to the background level of turbidity. Gordon

calculated the initial spreading velocity, taking into account the ambient water velocity, to be 0.8 ft/sec. Within approximately 15 min the velocity had decreased to zero and the collapse phase was complete.

39. While the bottom turbid cloud was spreading it was also settling. Average settling velocities were calculated to be about 0.02 ft/sec, approximately that of a fine sand although the solids were 90 percent silt and clay. Gordon estimated that at least 80 percent of the dumped material was deposited within a radius of 100 ft and that 90 percent was within a radius of about 400 ft.

40. Other researchers have also observed the spread of dredged material during the collapse phase. Sustar and Ecker[13] distinguished four layers in the water column following dredged material disposal from a hopper dredge. The upper portion of the water column extending from 25 to 35 ft below the surface was unaffected by the dumping operation. This is approximately the draft of a hopper dredge. A turbid layer existed from 3 to 15 ft above the bottom. The depth and sediment concentration in the turbid layer depended on current velocities, tide, and sea states. When currents and sea state increased, the depth of the layer and concentration of sediment in the layer increased. On the bottom was a layer of fluid sediment 3 to 6 in. deep overlying a compacted sediment bottom.

41. Dumping from the hopper occurred while the dredge was moving at a speed of 4 knots. The time required for release of 3000 cu yd was 5 min. Current velocity was 1 knot over the entire water column. Observations by divers shortly after the dump showed that the maximum accumulation was only 2 in. Pre-dump estimates were that the maximum and minimum accumulations would be 2.5 in. when dumping occurred on a line parallel to the current direction and 0.25 in. when released perpendicular to the current. Horizontal displacements for the maximum and minimum accumulation conditions were predicted to be 100 and 1700 ft, respectively.

42. Turbidity, or density flows of sediments released from dredging operations, has often been observed. May[14] has reported on open-water disposal from channel and shell dredging by hydraulic dredges. Almost all the sediment settled very rapidly and was transported along the bottom as a separate flocculated density layer. The sediment that was not deposited immediately under the dredge was transported in the density flow. Concentrations of 10,000 mg/ℓ were found within 400 ft of the discharge point, and concentration levels over 1000 mg/ℓ extended out at least 1800 ft.

43. Masch and Espey[15] also observed the continuous discharge from a hydraulic shell dredge. The sediment was classified as silty clay and was composed of about 60 percent clay, 25 percent silt, and 15 percent sand and shell particles. Data obtained from bottom funnel traps compared with others at 3-ft elevation showed that the sediment moved as a density current. Sediment concentrations 6 in. from the bottom were as high as 150,000 mg/ℓ; as the distance from the dredge increased, the thickness of the layer decreased although the concentration remained high. The density current was well defined even at distance greater than 1500 ft. At a distance 8600 ft from the dredge, the density current had concentrations greater than 100,000 mg/ℓ, was about 8 in. thick, and was over 1200 ft wide. While these observations and those of May pertain to continuous open-water pipeline disposal in shallow water rather than instantaneous discharges from hopper dredges or barges, it is clear that under certain conditions, dredged material can be transported great distances in a density current.

44. Probably the first investigators to study in detail the movement of clay suspensions in water were Einstein and Krone,[16] who reported on laboratory observations concerning cohesive sediment transport of San Francisco Bay mud. The sediment contained more than half clay with the remainder essentially all less than 100μ in diameter. Flocculation was considered to be one of the most important factors in cohesive sediment transport. Naturally occurring

flocculation is an electrochemical process associated with clay particles. In all waters, and particularly in salt water, flocculation results in particles grouping together due to interparticle contacts. These larger particles then settle faster than would individual particles. The particles must be cohesive for this phenomenon to take place. Cohesiveness depends to a large extent on particle size, with clay particles (<0.002 mm diameter) being the most cohesive, silts (0.002 to 0.06 mm) having some cohesiveness, and sand and gravel (>0.06 mm) possessing none. In addition to cohesiveness, other factors affecting flocculation are the type and concentration of particles, the nature and concentration of dissolved salts, and the level of mixing energy present. Low flocculation mixing energy would not produce enough interparticle contacts and too high a level of mixing would shear apart particles previously driven together. Among the conclusions drawn by Einstein and Krone were:

a. When sediment concentration exceeded about 10 gm/ℓ in saltwater flocculation occurred rapidly and during settling an interface existed between what was termed fluid mud and relatively clear water above it.

b. The concentration at which the settling fluid mud becomes too great to readily allow flow (the onset of consolidation) was 167 gm/ℓ.

c. Fluid muds behave as Bingham fluids: that is, they behave as true liquids when the shear stress is above a critical value and as solids below that value.

d. Fluid muds can be transported by gravity flow provided that the bottom slope is sufficiently steep to start and maintain flow. Once started, a gravity flow of fluid mud could be maintained on a flatter slope than that required to get it started.

e. The flow of fluid muds probably is not affected by bulk flow of the overlying water.

f. At suspended sediment concentrations less than 300 mg/ℓ, very little flocculation will occur, but increases in mixing energy can increase flocculation even at this low solids concentration.

45. White[17] conducted laboratory flume studies to investigate the movement of dredged sediment as a density current. Using sediment from shell dredging areas in Galveston Bay, Texas, containing 50 percent clay with lesser amount of silt, sand, and organic matter, he observed that:

a. Both currents and sloping bottoms tend to increase the movement of a fluid mud, but the effect of the current is much less than that of the sloping bottom, indicating that gravity is the predominant force in the movement of density layers.

b. When a shallow dike was placed across the flume with an opening at one end, the layer flowed past the dike through the opening. If the dike were placed completely across the flume, the layer fell back until it increased in height due to the introduction of additional material and then flowed over the dike. Appreciable deposition occurred in front of the dike while the layer's progress was impeded by the dike.

c. A suspended sediment concentration of 2200 mg/ℓ was required to initiate density layer flow.

d. Under flume conditions of no flow and a 1 deg slope, the mud flow interface front was observed to move at a velocity of 2.2 ft/min.

e. Strong currents tend to prohibit the formation of density currents by turbulent mixing and sweeping the sediment away before it can build up to sufficient concentration for layer development.

46. As a result of their laboratory and field work (partly based on White's work), Masch and Espey[15] concluded that for a sediment layer to form, sediment concentrations greater than 10 gm/ℓ are required so that settling of the layer is hindered and the layer can remain in a fluid form. It was estimated that the mud layer must contain more than 80 percent by weight of particles smaller than 0.0625 mm (the upper end of the silt-size range) of which about 50 percent or more should be in the clay range. Even though settling is hindered in the mud density current, consolidation of the flocculated

particles takes place and the layer gains shear strength. Within a few days the layer usually has enough strength to resist the shear produced by low magnitude tidal currents and is no longer capable of being moved except by higher energy currents which may cause erosion and resuspension.

47. Field efforts to control the spread of the fluid layer by construction of a 4-ft dike indicated that flow past the dike provided sufficient turbulence to keep sediments suspended so that they could be moved by currents. A continous trench proved to be very effective as a trap to intercept and hold sediment presumably because the density layer would tend to flow to the bottom where stagnant conditions would allow sedimentation to occur.

48. In summary, cohesive dredged material will flow as a density current under conditions of solids concentration between 10 and 170 gm/ℓ, clay content greater than about 50 percent, and the presence of a driving force due to a slope or to a hydraulic head. The major force producing motion is gravity rather than currents, and the motion can be interrupted by physical barriers provided that the barrier is sufficiently large so that flow will not go over the top or around the ends.

49. Long-term dispersion. Long-term dispersion refers to mixing processes that occur after the convective descent and collapse phases have been completed and include eddy diffusion due to random currents, mixing by wind waves, and mixing by currents traveling essentially in one direction such as tidal currents. Each of these is a complicated phenomenon and all may be acting on the water column at the same time, making an estimate of the final fate of suspended dredged material very difficult. In this study two simplifications serve to make a discussion of the problem more manageable. First, since the

point of interest is the placement of dredged material within a specific site, the ultimate fate of suspended solids swept from the site is considered to be beyond the scope of this study. Similarily, only that portion which remains and perhaps its distribution within the site need be accounted for. Second, for simplicity, dispersion in this sense can be limited to particles that have not yet settled out. Those that have settled out and, for one reason or another, have become resuspended will be considered in the next section.

50. At the completion of the collapse phase, suspended solids subject to dispersion will be of two fundamentally different types. The first type includes those solids that are part of the density current and remain in suspension within perhaps a foot of the bottom. They will be highly concentrated and may possess some shear strength to resist transport by currents. Experiments by Einstein and Krone[16] and White[17] have shown that the upper concentration limit on a sediment suspension beyond which further density flow will not occur is the range of 150 to 175 gm/ℓ. These particles will continue to settle, but at a slow rate due to bridging of particles and the difficulty of water escaping through the increasingly small pore spaces between particles. By observing sediments settling in a laboratory cylinder, Einstein and Krone estimated that the fluid mud phase lasted only about 2 hr in still water, after which time bulk flow is no longer possible and consolidation takes place. Sediment concentrations that can resist a given shear by flowing water are shown in the following tabulation taken from Reference 16. These data indicate that once consolidation has begun, the fluid mud can continue consolidating at flow velocities higher than those likely to be encountered in the sheltered environment of a subaqueous borrow pit.

Average Velocity cm/sec	Shear Strength dynes/cm^2	Sediment Concentration g/ℓ
30	0.98	17
60	3.43	59
90	7.37	127
120	12.60	217

51. The second type of solids subject to long-term dispersion includes those remaining in the water column as a result of the dumping operation. As the cloud rapidly settles and spreads across the ocean bottom, eddies will spin off and carry solids out of the main cloud. The concentraion of solids remaining in the water column will be sufficiently low so that the solids will not have sufficient excess density to sink readily to the bottom and rejoin the main cloud. At the New Haven dump site, Gordon[11] found that a residual drifting cloud existed after the dump. Turbidity profiles defined the cloud to be approximately 30 ft thick and have a diameter of about 200 ft. Measurements of the solids content of the cloud indicated that the total amount of solids contained in the cloud amounted to about one percent of the material dumped. Even if this material had a settling velocity equivalent to that of a coarse silt (0.008 ft/sec) and the mean settling depth were 25 ft, then approximately 50 min would be required in still water for the particles to reach bottom. If a current of 0.5 ft/sec were present, then the particles would be swept 1500 ft away before they reached bottom, a distance outside a borrow pit in many cases.

52. In summary, particles remaining in the density current are not likely to be dispersed by ambient current and will consolidate at the point where the density current stops. Particles remaining in the water column after the dump probably represent

a very small portion of all materials dumped and are likely to be swept out of the dump site before they settle to the bottom, even if the local current is quite small.

53. Bottom transport and resuspension. Once dredged material has been placed in a borrow pit, it is essential that the sediment not be eroded and transported out of the pit as might occur during periods of different environmental conditions. From the viewpoint of erodibility, sediment may be generally classified as cohesive or noncohesive.[18] As the term implies, noncohesive sediment consists of discrete particles the movement of which, for given erosive forces, depends only on particle properties, such as shape, size, and density, and on the relative position of the particle with respect to surrounding particles. Noncohesive sediments are relatively large grained, tend to not be polluted, and will generally not be depostied in borrow pits due to the higher cost of borrow pit disposal as compared to other disposal options. However, if a cover were placed over a polluted silt or clay, the covering material would probably be noncohesive sand. Knowledge of the erodibility of this sand layer would allow decisions concerning the proper thickness and, ultimately, whether a particular covering operation may not be successful due to high erosion rates.

54. Cohesive sediments are those for which the resistance to initial movement or erosion depends on those factors cited above for noncohesive sediment and on the strength of the cohesive bond between particles. This resisting force may far outweight the influence of the characteristics of the individual particles. Because the water currents required to erode or scour cohesive sediments are generally greater than those for noncohesive sediment with approximately the same grain size, the rate and extent of scour depends on this property (cohesive strength) rather than on the properties of the individual particles. Once the cohesive bond

has been broken, the individual particles behave as noncohesive particles for which deposition, scour, and transport become functions of the properties of the separate particles or small groups of particles.[18] In addition, once resuspended, the hydrodynamic behavior of cohesive sediments is complicated by the effects of flocculation. Floc size distribution depends not only on the physio-chemical properties of the particles but also on the flow conditions themselves. This dual dependence makes the processes of erosion, transport, and deposition of fine sediment fundamentally different and considerably more complex than similar processes for non-cohesive sediment.

a. Scour criteria. Erosion and resuspension of noncohesive sediment is an important consideration for dredged material disposal in borrow pits only from a consideration of covering a completed deposit with a coarse-grained layer to minimize leaching of pollutants from the deposit and to protect the deposit from erosion. Noncohesive sediments will be considered first, however, because the erosion processes are less complicated and more thoroughly understood. Much of the following discussion follows the presentation of Graf.[19]

Several related approaches have been taken to explain the initial scour condition of a sediment bed. In general, they each consider the impact of the flowing liquid on the bed particles. From theoretical considerations, the velocity at which scour is initiated will depend on (1) the particles, their size, uniformity, shape, size distribution, texture, etc.; (2) the dynamics of flow; (3) slope of the bottom, if any; and (4) the angle of repose of the particles.

Qualitative observations of scour conditions in natural materials has led to the following conclusions:

(1) The laws of hydraulics governing the movement of loose materials are only distantly related to the better understood

laws governing aged or virgin sediments.

(2) Sediment in aged beds is composed of material of different sizes and, when the interstices are filled with smaller particles, the mass becomes more dense and stable and will be less subject to erosion.

(3) The velocity required to scour an aged bed will be greater than that required to maintain the same particles in suspension.

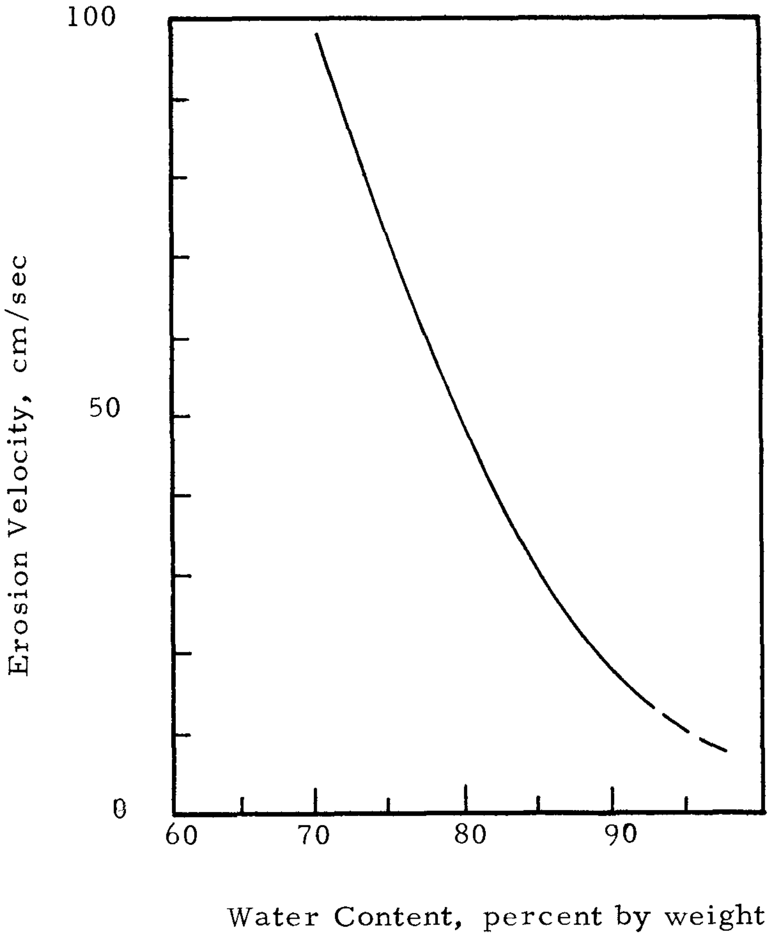
One of the most commonly referenced representations of erosion and deposition criteria is a diagram developed by Hjulstrom and presented by Graf.[19] This diagram is shown as Figure 1. The velocity term $\overline{u}$ is an average flow velocity at a distance of a meter or more from the bed rather than the velocity in the immediate vicinity of the bed. Graf presumed that this average velocity is about 40 percent greater than the bottom velocity. The diagram indicates that loose fine sand is the easiest to erode and that an average velocity of approximately 20 cm/sec (0.66 ft/sec) would be required. Greater resistance to erosion in the small particle range is due to cohesion forces. For a bed of aged particles having a diameter of 0.002 mm (silt-clay range) an average water velocity of about 5.2 ft/sec would initiate erosion. To achieve the same resistance to flow as the cohesive clay, a particle size of about 15 mm (fine gravel) would be required. A serious uncertainty of this type of analysis is the degree of consolidation or aging which has occurred with the silt or clay. However, if the erosion resistance indicated by this diagram is accurate, then covering of a silt-clay sediment with sand to prevent erosion will not have the desired effect since a sand cover would be more readily eroded than the silt-clay. Of course, if the purpose of the cover is to prevent leaching of pollutants from the silt-clay, and if water velocities are sufficiently low to prevent sand erosion, then the cover may still be of value.

Few investigators have studied the effect of aging of clay deposits on erodibility. Postma[20] has presented data resulting from experiments performed in a circular tank to establish the critical erosion velocity of fine-grained sediments. The critical erosion velocity was defined as the minimum current velocity at which sediment of a particular size began to move. This critical velocity depends on current velocity, tractive forces along the bed, roughness of the bottom, level of turbulence, and other factors. For simplicity, researchers usually describe the flow by an average velocity at a given distance near the bottom. Postma found that for particle diameters less than about 0.05 mm (upper end of the silt range) one set of curves was insufficient to describe the critical velocity relationship because of the effects of cohesion and the duration of consolidation.

Recently deposited, very loose and unconsolidated fine-grained matter is easily eroded. As the age of the deposit increases it will lose water and becomes more difficult to erode. Postma has described the consolidation process thusly:

> "The process of consolidation is essentially the result of the expulsion of water from the interstices between soil grains under load. The water escapes through microscopic channels interconnecting the interstices. During the process the soil particles are displaced relative to one another and form a more closely packed sediment of greater density and lower water content. In sands and most clays these movements are irreversible. Consolidation proceeds very rapidly in sand, but very slowly in silts and clays; the rate depends on the type of clay mineral and the degree of flocculation."

As the water content decreases, the critical erosion velocity increases. Data discussed by Postma[20] relating water content to critical erosion velocity are shown in Figure 2.



Mineral	Mineral Content %
Quartz	25
Chlorite	15
Feldspar	5
Expanded Illite	25
Kaolinite	15

Figure 1. Erosion velocity versus water content for a particular sediment[20]

Velocity measurements were taken 15 cm above the surface of the mud layer that had been allowed to settle from suspension. A water content of 91 percent corresponds to a consolidation time of 3 hr and 73 percent water content represents about 1 month's consolidation. Since the cohesive forces are largely dependent on the physical and mineralogical properties of the clays, the values shown are valid only for this particular clay. In addition, the critical erosion velocities found in these laboratory experiments may not be comparable to field values due to different velocity-turbulence relationships during erosion. Also, settling and consolidation in the experiments took place in still water, whereas at sea, currents and wave motion will influence the consolidation process. It was also suggested by Postma that since the natural water content of the sediment was about 40 percent compared to 73 to 91 percent in the experiments, the critical erosion velocity of the well-consolidated material might be considerably greater than 100 cm/sec and might approximate that for pebbles.

Partheniades[21] has conducted flume experiments to study the erosion and deposition of cohesive sediments. Two different conditions of the same sediment were tested. The first was natural material at field moisture and the second was a flocculated loose bed formed by deposition after the original bed had been placed in suspension. The composition of the sediment was 60 percent clay, 40 percent silt, and a very small amount of fine sand. The following conclusions were drawn as a result of the study:

(1) Although the macroscopic shear strength of the bed at field moisture was approximately 100 times as great as that of the flocculated bed, the minimum velocity at which scouring first occurred was approximately the same for both beds. The average rates of erosion were also of the same order of magnitude for the two beds.

(2) Erosion rates were independent of the concentration of suspended sediment.

(3) Erosion rates depended strongly on the average shear stress increasing very rapidly after a critical value of shear stress had been exceeded.

(4) There exists a limiting velocity above which all the eroded clay stayed in suspension and below which practically all suspended clay was deposited. The limiting velocity occurred at about 0.5 ft/sec for this sediment and was slightly lower than the minimum scouring velocity.

(5) A surface crust was formed, which showed a higher resistance to erosion than the clay. The crust was caused by cementation of silt and clay particles by iron oxides and by deposition of sand and silt that formed a continuous layer of relatively coarse particles.

A point raised by these researchers requires more consideration in light of the problem of filling of borrow pits with dredging material. The problem is to obtain an estimate of the time needed to achieve a certain degree of consolidation since the degree of consolidation has a direct effect on the critical erosion velocity of silt and clay. Very little information is available concerning this time/consolidation relationship. For the sediments in his experiments Postma[20] found a water content of 91 percent in 3 hr and 75 percent after 1 month. Under natural conditions the sediment had a water content of 40 percent, but the time needed to reach that value was not estimated.

Lambe and Whitman[8] have stated that the time required for a consolidation process is (1) directly proportional to the volume of water which must be squeezed out of the soil and (2) inversely proportional to how fast the water can flow through the soil. An expression relating these factors is given by Lambe and Whitman:

$$t \sim \frac{mH^2}{k} \qquad (2)$$

where t = time required to complete some percentage of the consolidation process

m= compressibility of the mineral skeleton

H= thickness of the soil mass

k= permeability of the soil

This relation indicates that the consolidation time increases with increasing compressibility, decreases with increasing permeability, increases rapidly with increasing thickness of sediment, and is independent of magnitude of applied stress.

The driving force for consolidation must be an applied stress to cause water to migrate upward through the sediment. This stress is a result of the excess density of the sediment particles compared to water. At the suface of the deposit, the stress will be zero, so consolidation will not take place and the surface will remain in a fluid state forever. As depth increases, the degree of consolidation increases because the stress increases. However, the time required to reach a given degree of consolidation is independent of the applied stress.

Although many of the factors affecting the time and degree of consolidation can be identified, very little field or laboratory data are available for consolidation of submerged sediment. It is apparent that sediment with a significant clay content will require long consolidation times, from a year to many hundreds of years, while coarse granular soil will become consolidated in a matter of minutes.[8] This great degree of variability, depending primarily on sediment characteristics, makes it impossible at this time to make meaningful estimates of consolidation rates and then to estimate the effect of the time factor on erodibility. Considerable additional laboratory and field work will be required in this area.

A second point raised by the work of Partheniades[21] is that factors other than grain size and current velocity will affect the erosion of subaqueous sediment. Each of the following effects tends to decrease the erodibility of sediments:

(1) Partheniades[21] has noted the formation of an iron oxide layer at the surface of the sediment deposit that caused cementation of silt and clay particles. Insoluble ferric iron deposits as soluble ferrous iron is oxygenated at the surface of the deposit.

(2) It was also noted by Partheniades[21] that hydraulic sorting of sediment can cause a continuous layer of relatively coarse grain particles to form on the surface. This sand layer acts as a continuous plate and may cause a significant increase in the resistance to erosion.

(3) Pratt et al.[6] have noted that tube-dwelling organisms inhabit organic sediments and thereby decrease erodibility by secreting cementing agents for formation of the tubes.

(4) Graf[19] has cited several investigations by others which indicate that the erosion resistance of a sediment containing a distribution of particle sizes will be greater than that of a sediment containing particles of only one size.

b. Currents at the ocean bottom. The intensity of water currents that may exist in the vicinity of the ocean bottom in a borrow pit dump site will, to a great extent, determine the feasibility of using the borrow pit for disposal of polluted sediments. If the normally occurring calm-weather currents are sufficiently high to transport appreciable quantities of dredged material out of the site before it can be deposited on the bottom, then dumping at the site cannot be considered feasible. A second criterion would be that the more intense storm generated currents must not be strong enough to erode and transport previously deposited dredged material from the site. Although exact values for these current velocities will depend on examining a particular borrow pit, order-of-magnitude estimates can be made and their effects examined.

There are five principal currents occurring on the continental shelves: (1) intruding ocean currents; (2) tidal currents; (3) meteorological currents; (4) density currents; and (5) discharge from rivers. A major difficulty in investigating ocean currents is that all may be acting at the same time, making it difficult to distinguish the effects of each type. In this study, it was considered helpful to differentiate current types by their time variability and intensity. Meteorological currents result from storms and are more intense, but are of shorter duration and less frequent than the other types. This is particularly true further offshore and in deeper water. Low intensity, relatively continuous currents will be effective in transporting sediments suspended in the water column, whereas the high-energy currents associated with storms may resuspend bottom sediments which otherwise could not be moved by lower energy currents. Low-energy currents could then transport these sediments from the dump site.

It would not be productive in this report to study each type of current in detail. For the lower energy, continuous currents it is only necessary to determine what general range of current speeds may be encountered in a dump site. Drake et al.[22] have studied bottom current velocities at ten locations near Santa Barbara, California, approximately 3 to 30 km (1.8 to 18 miles) offshore and in depths of about 25 to 150 m (82 to 492 ft). Current velocities related to tidal cycles ranged from 10 cm/sec (0.328 ft/sec) to greater than 50 cm/sec (1.64 ft/sec) with a mean value of approximately 25 cm/sec (0.82 ft/sec). Komar et al.[23] have discussed currents off the Oregon coast and point out that even at depths of 90 m (295 ft) and 165 m (541 ft), currents average about 10 cm/sec (0.33 ft/sec) and range from 0 to 25 cm/sec (0 to 0.82 ft/sec). Spectral analyses indicated that these currents were in part tidally induced.

During a study of the Wilmington Canyon on the East Coast of the United States, Stanley et al.[24] observed bottom current velocities up to 20 cm/sec (0.66 ft/sec) at a depth of 276 ft. It was concluded that even under calm sea conditions, continental shelf bottom currents are capable of transporting dense suspensions of fine-grained sediments. The authors considered that tidal effects were one of the dominant factors at work during that survey, but they doubted that tides alone were responsible for the transport of medium and coarse sand.

These few examples of bottom currents over the continental shelves are not intended to define the current velocities which might be anticipated in borrow pits, but they do indicate that even in water depths in exess of 150 ft, normal current velocities (due primarily to tides) of perhaps 10 to 20 cm/sec (0.33 to 0.66 ft/sec) may be anticipated. Under these conditions dredged material particles dispersed in the water column as a result of the placement operation will be transported. This may be seen in Figure 1, which relates the potential for erosion, transportation, and sedimentation to particle diameter and current velocity. For current velocities in the range of 10 to 20 cm/sec, all suspended particles less than about 2 mm (coarse sand) will be transported. This does not mean that all dredged material deposited under these conditions will be swept out of the borrow pit. The placement operation under some conditions will result in a high solids content density layer that will have some resistance to ambient currents. It is impossible to state at this time how effective the layer will be in decreasing dispersion due to ambient currents, but it is clear that solids remaining suspended in the water after placement may be swept from the borrow pit along with some fraction of the solids in the density layer.

A potentially even more serious problem exists concerning currents generated by storms. With the simple Airy wave theory it is possible to make approximate calculations of the bottom current velocity due to waves.[23] Airy's wave theory

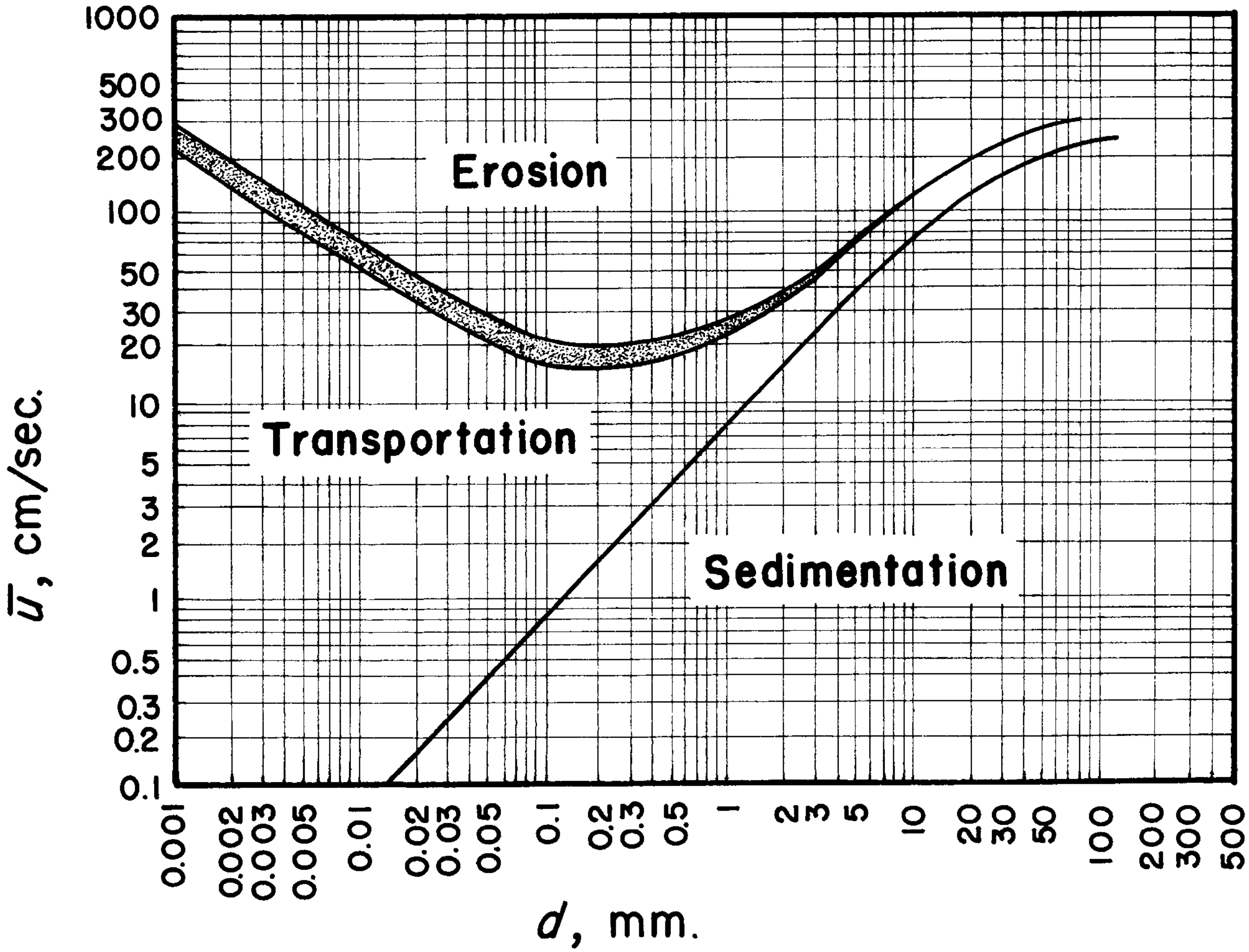


Figure 2. Erosion-deposition criteria for uniform particles[23]

produces an elliptical particle motion that becomes more circular near the surface and oscillatory at the bottom. The maximum horizontal velocity associated with this to-and-fro motion is given by

$$u_m = \frac{\pi H}{T \text{ sink } (2\pi h/L)} \qquad (3)$$

where u_m is the maximum velocity, H is the wave height, T is the wave period, and h is the water depth. The wavelength L can be approximated for deep water by

$$L = \frac{g}{2\pi} T^2 \qquad (4)$$

The velocity calculated is usually interpreted as the velocity at the top of the velocity gradient that develops near the bottom. With these equations it is possible to calculate the maximum velocity of the oscillatory motion under various assumed conditions. The results of such calculations are given in the following table:

Water Depth	Wave Period	Wave Height	Maximum Velocity u_m	
h(ft)	T(sec)	H(ft)	ft/sec	cm/sec
100	12	2.5	0.69	20.8
100	12	5	1.37	41.6
100	12	10	2.74	83.2
100	15	5	1.83	56.0
100	20	5	2.53	77.2
50	12	5	2.98	90.9
150	12	5	0.79	24.2

The values found are quite high and range in magnitude from the values previously cited for tide-related currents up to values four to five times as great. The conditions used in these examples are not extreme, and it would appear that during major storms considerably more intense waves are possible.

By themselves, these oscillatory currents will not result in any net transport of sediment since the water motion is only to-and-fro over small distances. However, if a linear current such as due to tides is also present, superimposed on the wave orbital motion, a net drift could result. The wind-generated waves can produce the power to place the sediment in motion and the linear current, at an intensity less than that required for resuspension, can produce a net sediment drift.

Field observations confirm that high bottom current velocities are associated with storms. Smith and Hopkins [25] have measured currents 3 m from the sea bed in 50 m of water off the Washington coast. During storms, velocities were encountered in the range of 60 to 70 cm/sec (2.0 to 2.3 ft/sec). The authors estimated that during one storm bottom velocities were sufficient to transport an eroded silt particle a distance of 110 km before the storm subsided. At another location in 80 m of water, twice within three months storms resulted in currents with peak speeds of 54 to 58 cm/sec (1.8 to 1.9 ft/sec). During the first storm, currents 3 m from the sea bed exceeded 40 cm/sec (1.3 ft/sec) for 36 hr, and during the second they exceeded 40 cm/sec (1.3 ft/sec) for 12 hr. Estimates of the amount of material eroded by severe storms ranged from a few millimeters to over a centimeter. These estimates are based on sediments that were well consolidated. Presumably, storm-generated currents of similar magnitude affecting unconsolidated sediment such as from a recent dumping operation, would result in considerably more transport.

Sternberg and McManus [26] also have measured bottom currents off the coast of Washington. They found that bottom currents during the winter months were sufficiently high to cause sediment movement for approximately 5 days/yr. A velocity of 70 cm/sec occurred for about one-half day/yr; since sediment transported as bedload is proportional to the third power of the velocity, this high velocity was considered to be responsible for significant quantities of sediment transport.

Again refering to Figure 1 which relates erosion, transportation, and sedimentation of sediments to particle size and bottom current velocity, it is seen that storm-generated bottom currents in the range of 20 to 80 cm/sec (0.66 to 2.6 ft/sec) are sufficiently high to erode and transport all unconsolidated particles less than about 10 mm in diameter. The size range includes almost all sands and some gravels. It may be concluded that dredged material deposited in borrow pits, whether covered or not, will not be able to resist many storm-generated currents and will be eroded and transported from the site at least in part. The rate of erosion during a particular storm and the number of days per year during which sufficiently intense storms will occur will depend on factors related to the borrow pit site (storm frequency and intensity and water depth) and the dredged material (degree and rate of consolidation).

55. Mathematical Dispersion Models. One of the most important factors in using subaqueous borrow pits for disposal of dredged materials is the dispersion of the solids occurring between dumping near the water surface and deposition of the solids on the bottom. For a borrow pit filling operation to be considered successful, essentially all solids dumped must be deposited within the pit. As the solids move through the water column, spreading of the cloud of solids will occur by dynamic forces and turbulent diffusion. Ambient water currents will deflect the cloud and transport it in the direction of water flow. It is necessary to understand the operation of these forces to make estimates of the degree of spread of the solids plume and then to investigate methods for control of the dumping

operation to minimize dispersion. For many of these purposes, dredged material dispersion studies can be carried out by the use of mathematical models; model studies allow great variation in physical parameters, are easily performed, and are relatively inexpensive.

56. A literature search yielded four models that were considered as possibly having application to the short-term precision dumping of dredged material in a relatively shallow ocean environment: the Edge-Dysart, the MIT, the Koh-Chang, and the Krishnappan models.

a. Edge-Dysart model. B. L. Edge and B. C. Dysart of Clemson University employed a combination of jet theory and sedimentation to develop a mathematical model of barged material dispersion.[27] In the first part of the model, a negatively buoyant jet discharged downward into a stratified environment is simulated. The second portion describes transport of material from the end of the jet to the floor of the ocean.

The model assumes that waste material is pumped from a circular outlet at some distance below the moving barge. The initial transport phase is that of a negatively buoyant jet and assumptions made concerning the jet flow include:

(1) Steady flow

(2) Incompressible flow

(3) Fully turbulent jet

(4) Longitudinal turbulent transport is less than convective transport

(5) Constant fluid properties

Differential equations are then developed for jet flow. Since the waste material is assumed to be negatively buoyant, it will sink toward the bottom. However, as the jet travels, it will entrain ambient water and may become neutrally buoyant before it reaches the bottom. It will then become stabilized at some intermediate depth, although the plume may oscillate about the neutral buoyancy position for a time due to residual momentum. It is implicit that the ocean floor is at a lower level than that achieved by the plume (since the model contains no provision for bottom encounter). Also, no dynamic collapse phase is considered. Termination of the jet transport phase results immediately in long-term diffusion. This may be a serious weakness of the model.

During the long-term diffusion phase, the most important factors are considered to be flocculation of colloidal-size particles and dispersion in the horizontal direction due to local turbulence. Although the authors discuss and stress the importance of flocculation, it is not clear how they have accommodated the effects of flocculation into the model. It is apparent that if a large portion of dredged material is in the clay-size range, then some accounting for flocculation effects will have to be made.

It was decided not to use the Edge-Dysart model in this study for two reasons. First, it does not describe short time interval dumping such as from a barge or a hopper dredge; and, second, for pump-out type dumping another model (the Koh-Chang model discussed later) was considered to be a better representation of that type of discharge.

b. MIT model. A three-dimensional analytical model has been developed by Christodoulou, Leimkuhler, and Ippen at the Massachusetts Institute of Technology (MIT) for the dispersion of fine suspended sediments in coastal waters.[28] The model has been adapted to computer solution and has undergone some field verification in connection with the New England Offshore Mining Environmental Study (NOMES) project. The authors conducted a number of test computer runs to investigate the effect of data inputs, representative of conditions in the Massachusetts Bay on model predictions.

The MIT model is based on long-term diffusion with consideration given to settling of solids and an ambient velocity field consisting of both longshore current and a tidal component. The sediments are assumed to be introduced into the water at a constant rate from a uniform vertical line source. The line source is considered to be far enough from the shore that land-sea boundary effects do not occur. Water depth is assumed to be constant.

The mathematical solution to the diffusion equation requires that steady-state conditions occur before meaningful results can be computed. For times shorter than that required for vertical equilibrium, the results will be unreliable. The authors showed that for conditions typical of Massachusetts Bay, the upper bound on the time for vertical equilibrium is about 25 hr, approximately two tidal cycles. This is the maximum time span after which reasonable results can be obtained. It should also be noted that the model is not valid in the immediate vicinity of the sediment source since vertical equilibrium must be established. Consequently, some travel from the source must occur before the model is reliable. It is apparent therefore that consideration of individual dumping events is not within the scope of the model. For these reasons the MIT model was not considered applicable to the dumping of dredged materials in subaqueous borrow pits.

c. Koh-Chang model. An extensive computerized mathematical model developed by R. C. Y. Koh and Y. C. Chang, considers the dispersion and settling of barged wastes disposed of in the ocean.[29] The model is an outgrowth of previous work by Koh on the problem of radioactive debris distribution following a deep underwater nuclear explosion in which long-term, three-dimensional diffusion was the principal phenomenon at work. The Koh-Chang model for barged materials considers three phases of dispersion: convective descent; dynamic collapse of the descending plume; and long-term diffusion.

Three methods of disposal from the barge were considered: discharge from a bottom-opening hopper barge; pumped discharge through a nozzle under a moving barge; and discharge into the barge wake. When considering the disposal of dredged material, it was apparent that only the first two cases are relevant. Wake discharge is employed when, as in the case of neutralization of acid wastes, a high degree of dilution is desired as quickly as possible. Since the placement of dredged material in subaqueous borrow pits or in designated dump sites will require that dilution be minimized rather than maximized, wake discharge will not be employed. The following discussion will consider only the other two cases. Additional model consideration, including a sensitivity analysis, is given in Appendix A.

(1) Barge Operation 1 - simple overboard dumping.

Dumping from a hopper, as described by this portion of the model, is the most common method of release of dredged material in open water. The model assumes that the cloud of material will descend as a result of its initial velocity and negative buoyancy. As it descends it will displace the ambient water around it, experience drag forces, and entrain surrounding water. Solid particles in the cloud will tend to settle out if the water is deep enough. This convective descent phase will cease either by encounter with the ocean bottom or by reaching a level at which the ambient water density changes rapidly so that the effect of the negative buoyancy is rapidly reduced. Provided that the water is deep enough, horizontal spreading will result as the cloud seeks a hydrostatic equilibrium with the ambient water. This effect has been termed the dynamic collapse. Following dynamic collapse, the plume will be dynamically passive and affected only by turbulent diffusion, advection, and settling out of solid particles.

Separate sets of equations are used to describe each phase of the overall model. In general, the equations governing the convective descent phase express the conservation of mass, momentum, buoyancy, vorticity, and solid particles. The dynamic collapse is described by the conservation of mass, momentum, buoyancy, and particles. Long-term diffusion considerations start from the general nonsteady state of three-dimensional conservation of mass equation. The output of the first phase is the input for the second. Similarly, the result of the dynamic collapse is the starting point for the long-term diffusion. Details of the mathematics and computer techniques employed to arrive at solutions to these expressions are complex. It is important to the conduct of this study to understand the types of information which must be inputed, the form of the data output, and, perhaps most importantly, any limitations on the application of the model that arise from the fundamental assumptions and methods of solution.

All dumped material first enters the model at the convective descent submodel and is in either a liquid or a solid phase. The liquid phase may include liquids and suspended solids, but the model assumes this phase to be always homogeneous and miscible with water. As the calculations progress, this phase will approach uniform mixing with ambient water throughout the water column. The solid phase, on the other hand, must include all materials that will eventually either settle to the bottom or float to the top. Any suspended solids included with the liquid phase rather than the solid phase will, by this model, remain "forever" in suspension.

The total waste volume is assumed to enter the model in a hemispherically shaped cloud with all materials uniformly mixed in that cloud. The initial radius of this cloud is an input value and thus must be set to satisfy the relationship:

total waste volume = $2/3 \ (\text{radius})^3$

The convective descent program allows this cloud to fall due to its own weight and initial velocity while, at the same time, it experiences resistance from the ambient and it entrains water. As a result the cloud slows down and gains buoyancy by entraining low-density water from near the surface. At the same time the cloud becomes diluted. If the ambient density gradient is zero (uniform density), the cloud's density will approach the ambient density as ambient water is entrained. If there is a positive density gradient, the cloud may entrain low-density water near the surface and then sink to a level of higher ambient density and there become neutrally buoyant. The convective descent submodel is ended either when the cloud achieves neutral buoyancy or when the lowest point of the cloud first hits the bottom.

A set of differential equations describes the convective descent process and are solved in the program by a Runge-Kutta method that gives the position and size of the cloud as functions of time. The cloud is assumed to retain its hemispherical shape so that size is defined by the radius. Position is defined by the location in a three-dimensional coordinate system of cloud centroid. The cloud also is assumed to remain uniformly mixed so that a single concentration for the liquid phase and each solid type can be specified.

Following convective descent the cloud undergoes dynamic collapse. The material entering the dynamic collapse submodel is the waste cloud that exists at the end of the convective descent, including the liquid phase and suspended solids, but excluding those solids which have settled out. Dynamic collapse assumes the cloud to be ellipsoidal in shape with a major axis (horizontal) and minor axis (vertical). As a result of resistance at bottom impact or at the stratified layer, the cloud spreads horizontally and collapses vertically. If the cloud achieves neutral buoyancy, it will, due to its own momentum, overshoot the neutrally buoyant point. Buoyancy then becomes a positive force so that the cloud is slowed and, under the influence of its weight, buoyancy, and momentum, tends to oscillate vertically about a neutral buoyancy point. As this occurs, vertical motion is suppressed so that the cloud collapses horizontally. During this motion the cloud continues to entrain ambient water and to experience frictional resistance from the ambient.

The set of differential equations that describe this dynamic collapse process are solved in the program by a Runge-Kutta method that gives the position and size of the cloud as functions of time. The cloud is assumed to retain an ellipsoidal shape so that size can be defined by its major and minor axes. Position is defined by the location of the cloud's centroid. The average concentration of the fluid phase as well as of each solid type is also determined and the distribution of this concentration over the cloud body is determined. The dynamic collapse submodel is ended when horizontal spreading due to diffusion becomes greater than that due to the dynamic collapse.

The diffusion submodel consists of several stages: one for diffusion of each solid type and one for the diffusion of the fluid phase of the dumped material. The fluid diffusion phase is initiated with the fluid cloud (fluid phase alone - excluding all solids) that exists at entry to the diffusion submodel. This cloud is defined in size, location, and concentration by the output of the dynamic collapse submodel. The cloud is diffused from the time at which the diffusion submodel takes over to the end of the specified modeling time. The solid diffusion stages are more complex. Since solids may have settled out of the waste cloud from as early as the convective descent submodel, it is necessary to track movements of settled solids from perhaps as early as the beginning of the convective descent modeling period. This is done by the diffusion submodel.

For each solid diffusion stage, the same procedure is followed. Beginning at time zero (start of dumping), any solids (of the type in question) settling out of the fluid cloud enter the diffusion model at, or shortly after, the time they leave the cloud. They are subjected to diffusion as well as falling and ambient effects (currents) from that point. Thus, it is possible that at each step of the diffusion calculation (up until the time of ending the convective descent and dynamic collapse periods) more solids will enter the diffusion submodel. At the end of the convective descent and dynamic collapse periods, all solids still remaining in the cloud are immediately thrown into the diffusion calculation.

The diffusion calculation continues tracking the solids from that point until the end of the specified modeling time. Throughout the diffusion calculation, the model keeps track of the solids deposited either on the bottom or on the water surface. It takes into account reintrainment and the probability of particles "sticking" to the boundary. This diffusion calculation is followed separately for each solid type included in the data input. Thus, the ultimate disposition of each type may be determined.

The set of differential equations required to describe the activity of the diffusion submodel is too complex to be directly solved by any practical scheme. A scheme (Aris method of moments) that projects moments of the concentration distribution instead of the concentrations themselves, however, is practical. This procedure allows specification, at any point in time, of the vertical distribution of each solid type, as well as the amount of each solid type that is deposited on the bottom. It does not specify the horizontal distributions of each solid type but gives only parameters of those distributions (i.e., means and standard deviations). If the form of the horizontal distributions are specified (e.g., assumed to be gaussian), concentrations at any point in the water may be estimated for each time point and each solid type. Likewise, the amounts of each solid type at any point on the bottom, and at any time, can be estimated for the assumed distribution.

(2) Barge Operation 2 - jet discharge. A second method of disposal from a barge is by discharge through a nozzle, either by gravity or pumping, while the barge is in

motion. It is probably true that only a small portion of dredged material is presently discharged in this way. A better method of more accurate placement on the ocean bottom might employ a long pipe to guide the material directly into the borrow pit. A model based on jet discharge would allow evaluation of this placement technique.

While the material is near the nozzle, the flow behaves as a sinking jet in a cross current. The jet entrains ambient fluid and momentum while experiencing a drag force. As a result, the jet grows in size and bends in the direction of the ambient fluid. As it travels, the material in the jet will be diluted by entrainment and particles will settle out. With time the jet effect becomes less pronounced and the material will spread out horizontally, followed by dynamic collapse of the jet and long-term diffusion. The equations describing the first, or jet convection, phase are those describing the conservation of mass, momentum, buoyancy, and particles.

The output of jet convection and dynamic collapse phases of Barge Operation 2 is used as the input to the long-term diffusion phase. The calculations and form of the output data for long term diffusion are identical with that already discussed for Barge Operation 1.

Koh and Chang had programmed the model to run on a CDC 6600. The program was obtained from EPA to be used in this study. A number of programming changes are required to enable the model to run under the conditions of dumping dredged material in shallow water. Although the model is theoretically sound, there appear to be programming logic errors in the way current is handled in the dynamic collapse phase and in the jet discharge mode. The nature of these errors is discussed in Appendix A. These must be resolved prior to extensive use of the model.

d. <u>Krishnappan model.</u> B. B. Krishnappan of the Canadian Center for Inland Waters has developed a mathematical model based upon experiments on the spreading rates of solid particles moving in a liquid medium.[30] Earlier work by others, such as Koh and Chang, assumed that the dredged material can be considered as consisting of a liquid medium whose density is equal to the equivalent density of the dredged material. Krishnappan's laboratory experiments indicated that the behavior of the solid particle cloud is very different from that of a liquid cloud and that the difference is a function of particle size. As the particle size decreases, the difference between the behavior of solid and liquid particle clouds also decreases, tending to zero in the limit.

Based on laboratory experiments, Krishnappan found that when a slug of uniform size particles was released in a homogeneous and stationary body of water, with zero initial velocity, the particles moved as a cloud with two distinct boundaries. The size of the cloud increased for some period and then maintained its size. Similarly, the velocity decreased until it reached a constant value equal to the settling velocity of individual particles. The first part of the descent was called the initial phase, where the cloud size grew due to entrainment, and the second was called the settling phase in which the horizontal cloud size remained relatively constant and the descent velocity equalled the fall velocity of the individual solid particles.

Using laboratory experiments, Krishnappan established coefficients to define the cloud growth during the initial phase and the settling phase. By superposition he was able to account for large particles settling out of the cloud while still allowing the remainder of the cloud to continue the initial phase (entrainment). Based upon this experimental approach, he was able to develop equations to predict the horizontal size of the cloud, the vertical descent velocity, and the height of mounding on the bottom. Using equations for a number of typical cases, he concluded that the settling phase will only occur for small dumps or in deep water (thousands of meters). Thus, for the case of borrow pit dumping, the initial phase is the only phase of interest.

The Krishnappan report has not been published. It would be of considerable interest to compare predictions using his model to those of the Koh-Chang model. Krishnappan's method is interesting in that it allows large particles to fall out vertically while still allowing the entrainment phase to go on. However, it does not provide for a density layer flow. Its simplicity is appealing, and it does not require a computer to perform the calculations.

A simple model such as this, if the settling coefficients are experimentally determined for given conditions, might allow predictions on a regional basis. The experimentally determined coefficients might also avoid the problem of attempting to establish the effects of dredge operation and material transport on the physical characteristics of the material. For instance, clay balls have been observed in a number of dump sites. General models such as the Koh-Chang will ultimately require that the modifications to the physical characteristics (i.e., shear strength or compaction) due to the dredging and transporting operation be known and inputed to the model. If these effects, along with others of interest, can be established through the use of experimentally determined coefficients, then a simple model such as the Krishnappan would have great appeal.

Operational Considerations

57. The operational cycle for borrow pit dumping involves a dredging operation, transit to the borrow pit site, navigation at the site during dumping, the dump operation itself, and the transit back to shore. In this section relevant parts of the operations cycle are examined: navigation at the disposal site and the dumping operation. In the next section, the disposal equipment aspects are examined in more detail.

Navigation

58. At the present time, dredged material must be dumped in approved dump sites, which, with the exception of disposal sites for toxic materials, are usually within 30 miles of the actual dredging site. Toxic dump sites may be 100 miles or more offshore.

59. In the case of hopper dredges, the navigational equipment is located directly on the dredge. For the barge situation the navigation

equipment is located on the tug that provides the propulsion to get the barges to the dump site. In either case the current navigation suite tends to be quite similar unless the dump site either is in sheltered waters of is a short distance from the dredge site. In the latter case small inland or river tugs may be used. These often have a minimum navigational capability, such as a two-way radio, a magnetic compass, and an inexpensive radar. For most dumping operations of interest to this study, seagoing tugs will be used that have a similar navigation capability to hopper dredges (described below) but without a Doppler sonar.

60. Existing hopper dredges and seagoing tugs are usually equipped with radar, a gyrocompass, a magnetic compass, a depth-sounder, and a Loran A receiver. In addition, the hopper dredges have Doppler sonar and most of them have Radio Direction Finders (RDF). Loran A provides a position fix capability of approximately $\pm$ 1 nautical mile (6076 ft).

61. Another method of navigation consists of using fixed markers to obtain a position and then running down a bearing from the fixed marker for a known distance. The bearing line can be established using optical, RDF, or radar bearings, and the known distance can be obtained from a Doppler sonar or other source of the data on ship speed. This method is sensitive to the distance from the fixed marker, the accuracy of the bearing line, and the knowledge of the speed over the bottom. Visual lines of bearing of $\pm$ 3 deg are realistic. Under good conditions a position-fix accuracy of approximately $\pm$ 1/4 mile (1500 ft) may be realizable. This approach is often used in the New York Bight by taking a fix on Ambrose Light.

62. The Coast Guard has seven light towers and a number of monster buoys (40-ft diam) that may be used to assist in finding dump sites. These navigation aids have radio beacons, strobe lights,

radar-enhancers, etc., on them. There are either light towers, light ships, or monster buoys in the following areas:

> Portland, Maine; Boston, Mass.; Buzzards Bay, Mass.; Nantucket, Mass.; Ambrose, N.Y.; Breton Reef; Chesapeake Bay; Savannah, Ga.; mouth of the Delaware River; Frying Pan Shoals and Diamond Shoals, N.C.; the Columbia River; and San Francisco, Calif.

63. In areas where the existing navigation aids are minimal, a buoy could be installed to provide visual or radar position fixes using off-the-shelf equipment and technology. This approach has been used in Long Island Sound. However, to be effective in bad weather, a radar transponder or large radar reflector is required.

64. The Coast Guard has the responsibility to provide dump site surveillance to eliminate short dumping (dumping before reaching the dump site) without a permit. Under P. L. 92-532, Marine Protection, Research, and Santuaries Act of 1972, Sec. 107(c), "The Secretary of the department in which the Coast Guard is operating shall conduct surveillance and other appropriate enforcement activity to prevent unlawful transportation of material for dumping, or unlawful dumping."

65. On Aug. 7, 1973, the Coast Guard distributed "Interim Surveillance and Enforcement Requirements for Ocean Dumping." A Commandant's Instruction will be promulgated in 1975. The Coast Guard's position is essentially one of carefully monitoring the dumping of toxic wastes and spot checking on the dumping of other materials. Toxic waste dump sites are far offshore, 106 miles in the case of the New York District. Surveillance is performed using aircraft, escort vessels, intercepting vessels, and ship riders, and checks are made of the dumping vessel's log. The Coast Guard spot checks for permits as well. Surveillance will be made of 100 percent of the toxic dumps and 10 percent of the dredged material dumps. The best surveillance

is in the San Francisco Bay area where the dump site can actually be monitored using the Vessel Traffic System.

66. Title II of the Marine Protection, Research, and Sanctuaries Act addresses the initiation of a comprehensive research program. Under this, the Coast Guard has begun a modest research and development program to investigate the feasibility of an automatic system to be placed on the dump vessel so that the dumping event can be monitored without the Coast Guard being present. Their program primarily addresses the offshore toxic material dump sites. The system is based upon Loran C.

67. Loran assist devices are being developed that take the Loran signal and either process and record the signal on board or retransmit it to shore for tracking purposes. The Coast Guard is also working on a Loran repeater and on a device that takes received Loran signals and calculates the range and bearing to any predetermined point. A system to track a dump ship and record its position every 10 min is being evaluated by the Coast Guard during FY 1975. These systems will be used on vessels dumping in the toxic dump sites.

Dump phase

68. Seagoing hopper dredges. The dump phase of operations for the seagoing hopper dredge begins after the loading cycle is completed and the vessel has proceeded to the borrow pit. As the ship approaches the borrow pit site, it will head for a point in the borrow pit area that has been prespecified in the form of either a Loran position, a radar position, a RDF position, or a visual marker such as a buoy. Regardless of the position-indicating method, the ship must come up to the indicated position and attempt to stay on it for the period of time required to perform the dump.

69. The approach to the mark will usually be made into the current in order to provide maximum steering control and maneuverability at or near zero velocity. Tidal currents are predominant around harbor entrances and enclosed bay areas but ocean borrow pits may be

far enough offshore so that tidal currents are minimal. Prevailing ocean currents should be small, or nonexistent, in a good borrow pit area. Wind-induced current is the only dependable aid along with the wind drag or sail effect acting on the ship. Since both of these factors are in phase with wind direction, the pilot will simply turn into the wind on his final approach to the mark.

70. The seakeeping characteristics of the hopper dredge are inherently good since for underway dredging, the vessel must be capable of control at low speeds over the bottom, in the range of 1 to 2 knots. The electric drive system for the propellers provides stable speed control all the way down to zero rpm in both forward and reverse directions. Twin props with separate controls provide excellent maneuverability. The ship can be turned on its own yaw axis at zero speed. The rudders on the hopper dredges are unusually large to insure positive steering at low water speeds. In currents up to 4 knots, the seagoing hopper dredge can be expected to hold a clearly defined position for a period of 1 to 2 hr. This operation presumes a competent pilot and an accurate Doppler sonar, or a visible buoy.

71. The seagoing hopper dredge empties its hoppers by bottom dumping or by direct pump-out. All 15 of the American hopper dredges are outfitted for bottom dumping, and of these, seven are equipped for direct pump-out.

72. Scows and barges. The procedure for dumping from scows and barges goes into effect after the tugboat arrives at the borrow pit. The tug will handle the scow by means of either a straight tow, by lashing to the port or starboard beam of the vessel and using a side tow, or by pushing from the stern. The straight tow and the side tow are the usual modes of towing; the stern push can be used if the barge is equipped with a deep notch on the stern. The latter is available only on the more sophisticated vessels.

73. In a straight tow the tug is secured to the barge with a

towline. If there is more than one barge in the tow, all are secured together with towlines or lashed together to form one large barge. The towline between the tug and the barge can be as long as 1000 ft. As the towing operation gets underway, the barge must be steered to prevent it from fishtailing. This is handled by the bargeman if the vessel is equipped with rudders. If not, a yoke is used in the towline to the barge.

74. In a side tow the tug is secured hard against the barge fore and aft, thereby allowing the tug to maneuver the vessel more positively. This type of tow entails far less line than a straight tow and is used primarily with single-barge tows.

75. During the trip to the dump site, the tug is in command of the tow and is responsible for all navigation and communications enroute. As the tow approaches the borrow pit, the tug will maneuver into the wind and current on its approach to the specified dump marker. Regardless of the type of tow and the number of barges, the tow behaves very sluggishly and is difficult for the tug to control and maneuver. The straight tow on a 1000-ft towline affords very little sideways or turning control because the tug must make large transverse excursions to steer the tow. If the barges or scows are equipped with rudders, their use will improve the control, but not all vessels are so equipped and those that are may not have any communications capability with the tug. The side tow is also difficult because the towing force is asymmetrically located so that the barge tends to turn as it is being towed. The tugboat captain can compensate for these factors to a certain extent, but he cannot be expected to hold the tow any closer than to a 100-ft radial error, or more, while the vessel is dumped. Upon dumping the first scow in the tow, the tug moves the tow ahead so the second scow is in position for dumping and so forth until all vessels in the tow have been dumped on the prescribed mark. When the scow or barge is over

the dump marker and the load is discharged, the dump extends over the total length of the hopper. In the case of a 400-cu-yd barge, the hopper length is approximately 200 ft; so that if the barge is centered on the mark, the dump extends 100 ft on either side of the mark.

76. The tug captain specifies the exact location where the dump is to be made and at the proper moment signals the scowman by a blast on the whistle. The scowman on the manually operated barge releases the ratchet for each set of bottom doors, thereby emptying each compartment. The time required for the compartment to empty will extend from less than a minute to several minutes depending upon the type of materials. When all compartments have been emptied and the dump completed, the tug begins the return trip and the scowman manually cranks up the doors for each compartment until they are closed.

77. The dump procedure for a clamshell barge is essentially as described above except that on the tug's signal to dump, the bargeman moves the clamshell lever to the open position. As the hulls open, the load begins to dump. When the dump rate reaches the proper level, the bargeman stops the opening of the clamshells by moving the lever to the off position. The bargeman can thereby regulate the rate of dump by the clamshell opening. Upon completion of the dump, the bargeman closes the hulls by means of the clamshell lever. During the return trip the bargeman attends to chores such as hosing down the barge and general cleanup.

78. Comparison of methods. There are critical differences in the use of barges and hopper dredges for borrow pit dumping. Hopper dredges are seagoing vessels that are capable of withstanding large seas with a minimum of discomfort or danger. Barges are substantially smaller and react to the seas more. While the navigation and dump-control levers on a hopper dredge

are an integral part of the vessel, the navigation equipment for a barge operation will be on a tug boat possibly hundreds of feet away from the barge, and there often is no direct communications between the two. In addition, there may be several barges towed behind a single tug. In documented cases, the last barge has broken loose from the tow and the tug boat did not know this until alerted some time later by the Coast Guard.

79. When the seas are rough, the barge operator has been known to dump the forward pocket to bring his bow higher out of the water or to dump the fore and aft pockets to achieve more freeboard. It has been common practice, amply documented by Coast Guard records and bottom surveys, for operators to dump short of the required dump site, possibly for safety, economics, or convenience. While this latter action could also take place with a hopper dredge, the motivation for doing so is less.

80. A hopper dredge is operationally suited for borrow pit dumping in almost every respect. It has the necessary capacity and speed, as well as the maneuverability and control for sea-keeping, and its dumping systems are effective from the standpoint of unloading the hoppers. As presently configured, hopper dredges cannot release the load at depths greater than their draft, resulting in a near-surface dump.

81. Barges and scows may be used for borrow pit dumping under certain conditions. They have the necessary storage capacity and transit speed is provided by the tugboat. They are more difficult to maneuver and control than the hopper dredge, but the dumping action is simple. Major factors in their favor are their availability in large numbers and that little or no training is required to operate and tend them. Like the hopper dredge, however, these vessels cannot discharge

dredged material at a depth greater than their draft. Their biggest shortcoming is the almost total lack of direct control that the tugboat captain can exert over the moment of dump initiation. Another restriction is the uncertainty of scow position, relative to the borrow pit, since the navigation capability exists on the tugboat, rather than on the dump vessel. Finally, it is almost impossible to hold the barge into position over the dump site, in any significant wind or current. This means that, should the material hang up in a pocket, the dump vessel will quite likely move off the desired dump point before the material is released.

Disposal Equipment

82. The vessels and equipment that can be used for ocean dumping in borrow pits are barges, scows, and seagoing hopper dredges. The requirement for usage is simply that the vessel be able to transport an adequate load from the location of the dredging operations to the borrow pit, to position itself relative to the pit, and to dump the load into the pit. The applicability of barges and scows is obvious since the requirement matches their normal functions with the possible exception of positioning capability. The hopper dredge is a potential borrow pit user because of its storage capacity and dumping capability. None of the stationary dredge types (i.e., hydraulic suction and clamshell) are considered to be disposal equipment because they lack storage and dumping capability. It is also very unlikely that a hydraulic suction dredge will discharge directly through a pipeline into a coastal borrow pit because of the usually large distance between dredge and pit, the obstruction of navigable waterways by the pipeline, the potential pipeline damage from storms, and the high-energy bottom usually found nearshore.

Hopper dredges

83. General. The modern seagoing hopper dredge is a self-propelled, self-sufficient hydraulic dredging plant that is designed for ocean navigation and work in coastal waters. It is used principally on the improvement and maintenance of navigation channels where wave action or heavy traffic does not permit the use of stationary dredges. It operates underway and requires no anchors or other mooring systems during dredging. It can dock and undock without tugboat assistance. In appearance the seagoing hopper dredge has the lines of a ship (rather than a barge) whose amidships cargo spaces are large storage hoppers. The hopper dredge pumps bottom sediment into its hoppers through trailing dragarm suctions. When loaded it proceeds under its own power to a disposal area where the dredged material is disposed of by gravity dumping through gates in the bottom of the hoppers. In recent years one such dredge has been modified to pump directly overboard in a sidecasting mode without filling hoppers and others have been equipped to self-unload or pump-out to permit the pumping ashore of dredged material from the hoppers through discharge pipelines.

84. The Corps of Engineers owns and operates the hopper dredges used for navigation channel dredging in this country. At the present time, the Corps owns 15 hopper dredges with hopper capacities ranging form 500 to over 8000 cu yd. Seven of the hopper dredges are equipped for direct pump-out operations and one of the seven is equipped for sidecasting as well.

85. Applicability to Borrow Pit Dumping. The capability of hopper dredges is consistent with the concept of borrow pit dumping. The hopper dredge can transport large loads over long distances from the dredge site to the disposal area and do it in less time than by any other method. The hopper dredge can

transit at speeds as high as 16 knots and therefore can travel up to 10 to 15 miles to the dump site before the cyclic costs become prohibitive. Most borrow pits will be in water deep enough to accomodate the hopper dredge, the largest of which draws 31 ft of water. The borrow pit may have been dug originally by a hopper dredge. The seagoing hopper dredge does not obstruct navigable waterways; it can transit and dump in high sea states; and it can remain on station for as long as two weeks before returning to port for refueling and stores.

86. On arrival at the disposal area, the ship lines up on the desired dump course and starts its run at low speed. The dump is accomplished by opening the bottom gates sequentially or all together, allowing the load to discharge by gravity in a line along the dump track. At the conclusion of the dump, the ship returns to the dredging site for further loading.

87. Characteristics. The specifications for domestic hopper dredges are of importance in considering the dump accommodations required for the ship at the borrow pit locations. The following set of specifications are for the ESSAYONS, which is the largest domestic hopper dredge in the Corps of Engineers' fleet. The reason for using the largest ship as a reference is that if the borrow pit dumping facility can accomodate the largest vessel, it can probably handle the entire fleet.

	Specifications of ESSAYONS
Overall length	525 ft 2 in.
Beam	72 ft
Maximum draft:	
Light	20 ft 6 in.
Loaded	30 ft 8 in.

Displacement:	
Light	9,516 long tons
Loaded	22,410 long tons
Maximum vessel speed:	
Light	17.3 mph
Loaded	16.0 mph
Dredge pump capacity (each of two pumps)	50,000 gpm
Hopper capacity	8,270 cu yd
Maximum dredge depth	65 ft

88. Dredge piping system. In all hopper dredges the basic function of the dredge piping system is to transport the dredged material from the bottom into the hoppers. This is accomplished by drawing the mixture into the draghead as it trails along the bottom, up through the hinged dragarm, through the pump and distribution piping, and finally into the hoppers. The older dredges use a single pump for both port and starboard dragarms because this is the most efficient arrangement for dredging. The two drags are valved and they tee together at the suction of the pump so that either or both can be operated. The newer dredges and some modified older dredges are equipped for pump-out as well as normal dredging. The plumbing system uses two dredge pumps with separate drives, and it is designed to provide the following modes of operation:

a. Dredge through either or both drags and discharge into hoppers.

b. Dredge with one drag and discharge through the other drag.

c. Pump-out hoppers using the two pumps in parallel and discharging through two overboard pipelines.

d. Pump-out hoppers using two pumps in series and discharge through either port or starboard overboard connections.

89. The pump-out system incorporates a water-jetting system that fluidizes the load at the bottom of the hopper, thus enabling it to be drawn into the collection piping. Seawater is added to the suction flow to further reduce the solids ratio to 10 to 15 percent. This is implemented by teeing into the suction leg of the collection system a seawater main that connects directly to a hull-mounted sea chest. Maximum flow rate is obtained by operating the two pumps in parallel and discharging ashore through two pipelines. This arrangement is only feasible with short pipelines since the delivery pressure is limited. Maximum pressure is developed by operating the two pumps in series and discharging ashore through a single pipeline. This arrangement provides the capability of delivery over a greater pipeline distance.

90. The most recently built hopper dredge, the MACFARLAND, is equipped to dredge, pump out, and sidecast the dredged material. The plumbing arrangement is the same as for the pump-out configuration outlined above. In addition, the piping provides for the dredged material to be discharged directly overboard through a pipeline that is supported on a revolving sidecasting boom. The boom can deposit the material up to 163 ft outboard of the side of the dredge.

91. Loading procedures. The loading procedure is generally concerned with the setting and handling of the drag system as well as the filling of hoppers. During a normal dredging run, the drag system is adjusted automatically or manually to follow the bottom contour and maintain the bearing force of the draghead on the bottom. The bearing force will influence the ratio of solids in the mix and will have a different value for the optimum mix depending upon whether the bottom material is sand or mud. The draghead is equipped with vent ports that can be opened or closed to further

adjust the amounts of water in the mix. The draghead is also outfitting with a debris and stone guard to limit the particle size of ingested solids. Large stones or pieces of debris can damage or jam the pump; they can damage the discharge system as they roll through the pipes and fittings; they can also settle out and plug the system. The largest object the pump can safely pass is one-half the pipe size. The spacing of the debris guard grids is approximately one-third the pipe size. For example, the system pipe on the dredge GOETHALS is approximately 30 in. in diameter. The debris guard blades on the draghead are spaced at 10 to 12 in. This indicates the size of the largest possible solid object in the hopper load.

92. Sand dredging is carried out with the hoppers continuously overflowing. Because of its high settling velocity, the sand is trapped in the hoppers while the lightened residual mixture passes over the weir and out the overflow channels, which exit from each side of the hull at or just below the waterline. In a typical situation the suction mixture carries 10 to 15 percent solids (by weight) while the overflow mixture contains as little as 0.26 percent solids. The collection efficiency is seen to be quite high.

93. In most applications the hopper dredge does not pump beyond overflow when it is dredging mud or silt. The settling velocity of these particles is so low that they cannot be trapped in the hoppers during an overflow condition and the mixture flows through the hoppers and out the overflow system, generating a turbidity plume that may extend several miles. The normal procedure is to dredge only to overflow so that the hoppers are full and to ride the draghead well into the bottom to maximize the solids ratio. Under these conditions the solids ratio can be approximately 40 percent by weight.

94. Offloading procedures. Once the hopper dredge is on station and seakeeping, dumping operations begin. The hoppers are emptied one at a time beginning with the aft hopper, then the forward hopper, alternating back and forth so the ship does not get far out of pitch trim. Each hopper is usually open from port to starboard (i.e., no longitudinal bulkheads through the hoppers) so as the load empties, care must be taken not to let it hang up or arch on one side of the hopper because it can cause the ship to list seriously. If more than one hopper hangs up on the same side simultaneously, the list can become dangerous and necessitate shifting ballast to prevent possible damage. This is the primary reason why hoppers are emptied one at a time rather than all at once and water-jet systems are installed in hoppers to break down the load should it arch. Any load that is permitted to arch represents a further hazard because the arched load can collapse suddenly. The resulting impact can damage ship structure directly and can set up vibrations that can cause hull plates to fail in fatigue. This phenomenon has been experienced in practice.

95. Consider the case where the load is emptied by bottom dumping and the material is mud and silt weighing 1100 to 1200 gm/ℓ. This mixture flows smoothly and will likely typify the material to be deposited in ocean borrow pits. The dump operation is initiated by opening all the bottom doors in the first hopper. The actuation mechanism is hydraulically driven so that the door opens in a matter of seconds and the load starts to empty immediately. At the beginning of dumping, the free surface in the hopper can be as much as 20 ft above the waterline and it is this head that causes the mixture to start flowing out through the bottom opening. The free surface in the hopper starts to fall and the discharge flow becomes established.

As the falling level in the hopper approaches the ship's waterline, which is itself falling due to lightening, the dynamic characteristics of the moving mass in the hopper cause its level to move past the ship's waterline and come to a dynamic minimum down close to the bottom opening. If the doors are left open, seawater flows back in to fill the hopper up to the ship's waterline. This action serves to flush the hopper clean of solids. In the interest of minimizing the volumes of water remaining in the hopper, the bottom doors may be closed at the instant the level bottoms out. This can be done when the mixture is clean and does not stick to the hopper surface. Otherwise, the bottom doors are left open until the hopper has been washed down, and when closed they trap the water remaining in the hopper up to the height of the ship's light waterline. This volume represents less than 10 percent of the total available hopper volume and the residual water is carried back to the dredging site on the return trip. The remaining hoppers are each emptied in the same manner and washed down in preparation for the next loading cycle. Each hopper will require approximately 5 min to empty and 15 min to wash down, a total of 20 min per hopper. The total dump time will therefore be 1 hr and 20 min for four hoppers.

96. If the material is coarser than that described above, the bottom dumping operation becomes more complicated and requires considerably more time. After the bottom doors are opened, sticky, coarse material will tend to adhere to the hopper surfaces and to arch readily. The discharge action is not smooth and uniform, but is rather sporadic in the form of repeated arching and collapse as promoted by the system of water jets. After all the bulk material discharges, the hopper is washed down. Each hopper can take as much as 30 min to empty and 15 min to clean. The total dump may require 3 hr for four hoppers.

97. A number of hopper dredges can also be unloaded by pumping out the hoppers. The direct pump-out system enables the hoppers to be emptied completely regardless of the type of dredged material in the hopper. The hopper mixture is drawn into a collection piping system through ports that are located at the bottom of each hopper. The hopper ports are each valved and connected into two longitudinal collection manifolds (port and starboard) that run back to the inlet port of each dredge pump. Figure 3 shows the arrangement. Before being drawn into the collection system the dredged material is diluted by means of an array of six jets in the lower part of each hopper. The jet system is supplied with seawater through its own pumps. A seawater main tees into the collection system so that the mixture can be further diluted before passing through the dredge pumps. The dredge pump piping system is arranged so that the mixture can be pumped through one or both overboard discharge connectors.

98. After the piping system is set up, the start-up procedure can begin. The jetting system is turned on in the first hopper to be emptied and the valves for the port lines are opened. The jetting nozzles are located low in the hopper where they discharge seawater to fluidize the load so it will more readily pass into and through the collection piping. The jetting system is essential for coarse, sticky materials. The mud or silt material that will likely be deposited in borrow pits is fluid enough so that jetting will probably not be necessary. The dredge pumps are turned on and the fluid mixture is drawn into the collection system by the jet pump effect created by the seawater flow through the mains. As the hopper discharge flow establishes itself, the seawater valve may be adjusted to maximize the discharge flow. Once the hopper is empty, the sides are cleaned with wash-down nozzles after which the jetting and wash-down systems

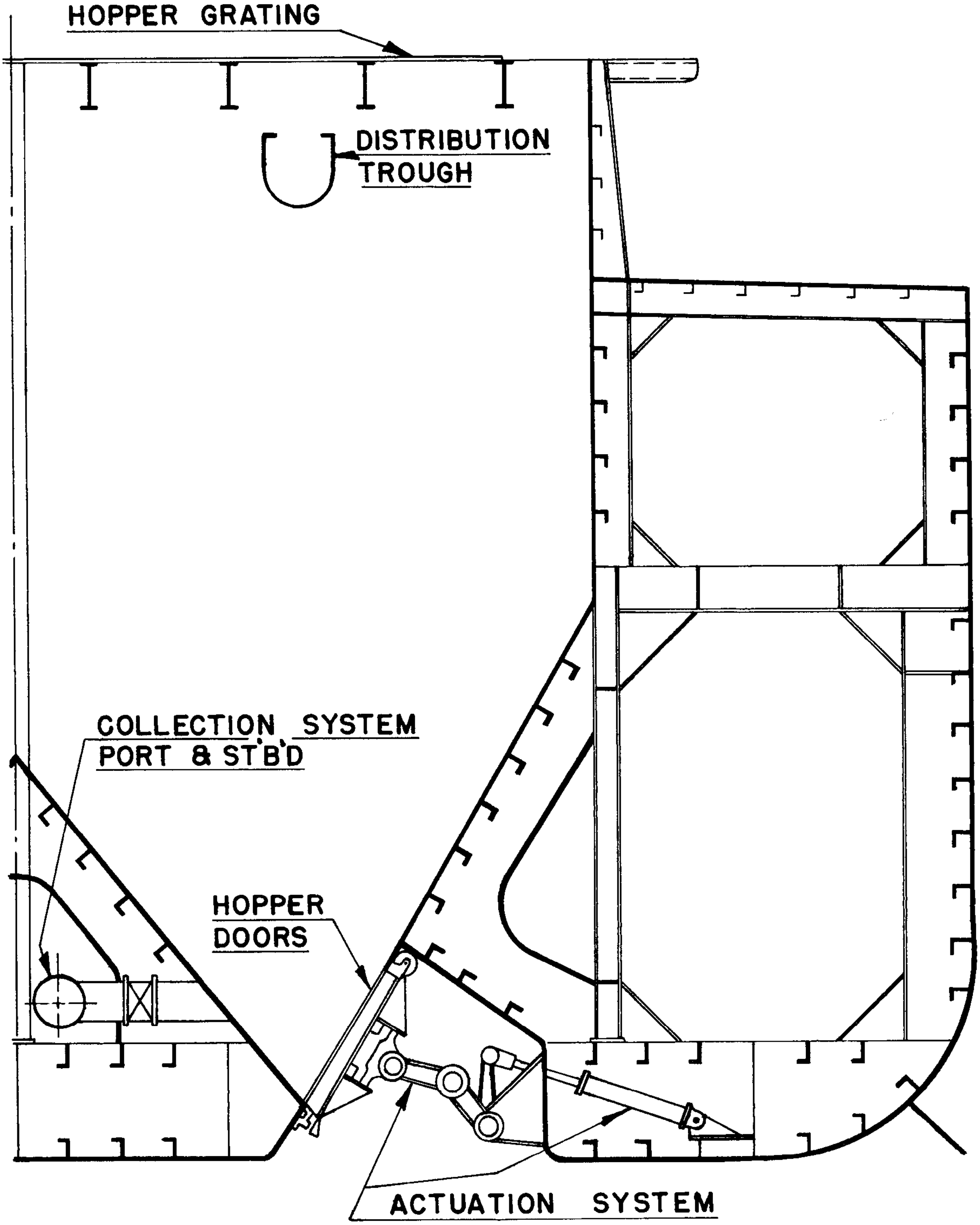


Figure 3. Section through hoppers of a typical hopper dredge

are shut off and the collection ports closed. The empty hopper is left reasonably clean and with very little residual water. The second and subsequent hoppers are processed in the same manner.

99. The unloading time for the pump-out mode is comprised of the times for set up, start up, pump out, cleanup, and shutdown. Setup time runs approximately 15 min per load, start up requires 5 min per hopper, and pump out will vary according to the material. For most borrow pit dump materials, the pump-out time will be approximately 15 min for the entire load. Cleanup and shutdown require 20 min per hopper. The total unloading time for four hoppers is thus 2 hr and 10 min.

100. At the present time hopper dredges are not configured for pump out at a borrow pit. To adapt the pump-out system for borrow pit dumping, an elbow and vertical pipe assembly must be added to each overboard discharge connector to direct the pumped material over the side and downward. If this change were made, the following procedure would be followed to unload the hoppers through the pump-out system. The first step would be to set up the plumbing for the operation. The valves in the collection system would be set so that the mixture from the hoppers is piped to the suction side of each dredge pump. The mixing valve would be opened in the seawater main that tees into the suction pipes. The discharge lines from the dredge pumps would be arranged to deliver the flow to each of the two overboard discharge connections and the dredged material would then flow through the elbow and downward into the water. It is necessary to direct the flow downward and under the water to minimize the width of the turbidity plume.

101. In Part IV this idea of pump out is expanded and presented as a pump-down concept. There is little reason to believe that pump out at the surface would enhance the capability of the hopper dredge when using borrow pits.

Barges and scows

102. General. Barges and scows traffic the ocean dump sites and disposal areas more than any other vessel type and could be the most frequent user of ocean borrow pits. They are designed to transport bulk materials to a disposal area and to dump the load upon arrival at the dump site. They are generally not powered and hence require tugboat services to tow or push the vessel to its destination. Barges and scows are flatbottomed and straight-sided except for the bow, which is sloped to deflect head seas. The water plane is rectangular and of sufficient dimensions and area so that the vessel is extremely stable and of shallow draft even when fully loaded. These vessels all unload by bottom-dumping mechanisms in the form of clam shell hulls or trap doors. The controls for dumping are mechanical or hydraulic and are actuated manually or remotely by radio control. Regardless of the type of control system, the barge or scow is manned by a bargeman or scowman. The vessel is always equipped with at least a shed for his protection against the weather.

103. Specifications. The specifications outlined below are typical for barges and scows available today in the range of capacities noted. The data are intended for reference in determining accommodations at the borrow pit location.

	Typical Barge Specifications		
Capacity: cu yd	200	1000	4000
short tons	270	1350	5400
Overall length, ft	90	150	240
Beam, ft	20	35	54
Depth amidships, ft	9	15	24
Draft: Loaded, ft	7	12	20
Light (open), ft	3	6	9
Light (closed), ft	2	3	4

104. Types of barges. Although barges and scows of the same capacity have approximately the same overall dimensions and shape, they are classified further according to their hull type. The majority of these vessels have a single hull with bottom doors that open to dump the load. Most modern barges are designed with split or clamshell hulls that hinge open to release the load through the resulting bottom opening. The single hull scows are partitioned into a number of compartments, usually six for the average-sized vessel, each outfitted with a set of bottom doors. The scowman can thereby empty the compartments selectively so that he has control of the trim of the vessel during dumping. The bottom door system usually consists of a pair of doors (port and starboard) running the length of each compartment and hinged along the outboard edges so that they open downward. The doors are held closed by tension chains or cables that are attached at each end of each door (four per compartment) and are fed over a winch drum that extends the length of each compartment. The winch drum is driven manually through a worm set and ratchet. The bottom door system has been modernized in more recent scows by incorporating sliding bottom doors that are actuated hydraulically. This eliminates the manual labor required to winch the doors closed on the older vessels.

105. The clamshell barge has a split hull whose port and starboard halves are hinged together so that the hull behaves like a clamshell (i.e., it is closed to fill and opened to empty). The hinge axis runs longitudinally in the midships plane at deck level and well above center of gravity locations. The hinge lugs are located at the bow and stern so that the hopper area is clear. When the hulls are closed, hydrostatic pressure acts to keep the clamshell closed. When opened, the clamshell halves are held open by buoyant forces. The clamshell mechanism is actuated hydraulically by means

of cylinders. The hydraulic controls are centralized in a small pilothouse at the stern of the vessel. The pilothouse in most cases is attached to one of the hulls and rotates with it as the clamshell opens. On more sophisticated systems, the pilothouse is connected to both hulls in a manner such that it remains vertical as the hulls open.

106. Dump scows and barges have little or no equipment aboard for basic power, communication, and navigation purposes. This is because there is no need or if there is a need, it is satisfied in other ways. The manually operated dump scow has virtually no auxiliary equipment on board. The dump system is completely mechanical and manually operated by the scowman. Navigation services are provided by the tugboat operator, who is responsible for towing the scow to the proper dump site location and back to port. Communication between the tug and the scow is by visual and audio means. In particular, when the scow arrives at the dump site, the tugboat signals the scow by a blast on its whistle and the scowman proceeds with dump operations. More than likely no power is available in the scowman's shed; he even depends on a kerosene lamp for lighting.

107. On clamshell barges a power system is required to drive the hydraulic system, but otherwise the needs are no more than for the manually operated scow. The most basic power system will use a small diesel engine that drives the hydraulic pumps directly as well as an auxiliary electrical system. The latter powers hydraulic solenoid valves and simple functions such as lights in the pilothouse.

108. Dumping considerations. The barge, or scow, is towed to the dump site by a tugboat. When the manually operated scow is in position and ready to be dumped, the scowman releases each set of hopper doors by knocking out the ratchet dog that secures the

cable drum containing the tension cables that hold the doors closed. He first releases the aft hopper and walks to the bow where he releases the forward hopper. He continues this alternating pattern until the last hopper is discharged in the midships area. This procedure prevents the vessel from going far out of trim during a dumping cycle. In the process the scowman walks approximately three deck lengths on a scow with six hoppers.

109. The load will move out of the hopper smoothly for any of the materials anticipated for borrow pit disposal. This is because the hopper is wider than it is deep and the door opening is sufficiently wide that the hopper walls are at a steep angle. As soon as the bottom doors open the load begins to empty.

110. The total unloading time for a manually operated scow consists of the time to release and dump one hopper and to walk back and forth over the deck route. On a 4000-cu-yd vessel the scowman takes approximately 5 min to walk the route, while a hopper load is released and dumps in 1 min. The total dumping time is therefore 6 min per scow.

111. When all compartments have been emptied and the dump completed, the tug begins the return trip. The scowman hoses down the hopper and manually cranks the doors closed during the trip. The freeboard and trim of the lightened scow is such that little or no water gets trapped in the bottom of the compartments.

112. The clamshell barge eliminates practically all of the manual effort and it empties the entire load in one operation. At the signal for "on-station", the bargeman moves the control lever to open and the hydraulic pistons rotate the shells open to release the load over the entire hopper length. The design of the shells is such that when open, the walls are at a steep angle and the opening (25 percent of beam) is sufficient that the load moves out without

hanging up. The maximum opening of split barges is approximately one-fourth of the molded beam. Thus, in the case of a 4000-cu-yd barge whose beam is 54 ft, the maximum bottom opening will be approximately 13 ft. It is noteworthy that the entire barge opens at once and dumping occurs along the full length of the hopper. Consequently, compartmental bulkheads serve no important function and hence are rarely found in clamshell barges. Upon completion of the dump, the bargeman closes the hulls by means of the clamshell lever. In the closed position the hulls trap little or no water in the bottom of the hopper.

PART III: FEASIBILITY OF BORROW PIT DUMPING

113. In Part II the factors affecting borrow pit disposal were examined in considerable detail. This part examines the feasibility of borrow pit dumping in light of these factors and draws conclusions as to the feasibility of using existing equipment, essentially without any modifications. The information is presented in the following order:

- Dredging and transportation to the site
- Navigation in the borrow pit area
- Short-term behavior of material during dump
- Long-term behavior of material after dump

Dredging and Transportation to the Site

114. Borrow pit dumping does not place any special requirements on the dreding phase of the operation. For the purpose of this report, it was presumed that the material being dredged is fine-grained and polluted or else precision placement would not be necessary. The material can be dredged using any of the three types of dredging equipment (bucket, hydraulic pipeline, or hopper dredge) and either barged to the site or transported in a hopper dredge. Since the material will be fine, undoubtedly it will have been dredged in a manner to minimize the turbidity plume, such as restricting the hopper dredge overflow, resulting in a relatively fluid load of material with a high water content.

115. Transit to the borrow pit area will be either by hopper dredge or by barges and a tugboat. On the way to the site, the material consolidates and increases the shear strength of the material. These factors will increase during the transit, giving changes in the material longer to take place if the dump site is far from the dredging site. On the hopper dredge these

physical changes may be affected by vibrations induced by multiples of the propeller blade rate and pitch, roll, and heave of the ship. In the case of barges, blade-rate vibrations do not apply.

116. Navigation during the transit to the dump site will be provided by a combination of systems. The hopper dredge will use existing landmarks (i.e. light platforms, buoys, etc.) to obtain a fix near the borrow pit and then, using a radar range and bearing, or a gyro compass heading and Doppler sonar speed-over-the ground, will move to the vicinity of the borrow pit. Loran A fixes will be used to find the area of the borrow pit. With radar or gyro compass and Doppler sonar, a realistic estimate of the accuracy with which the vessel can locate itself is about $\pm$ 0.25 nautical miles (1500 ft). With Loran A the accuracy is reduced to approximately $\pm$ 1 nautical mile (6076 ft).

117. In the case of a tug towing a barge, the same navigational capability exists except that the tug will not usually have a Doppler sonar so that the range must be established using the radar or a knot meter, which measures speed relative to the water rather than to the bottom. This introduces an uncertainty due to currents that may be present. As in the case of the hopper dredge, if no fixed landmarks are available, the Loran A accuracy will be about $\pm$ 1 nautical mile (6076 ft).

118. While transiting to the borrow pit, there is approximately a 10-percent chance that the Coast Guard will provide surveillance to ensure that a dumping permit has been issued and that the dump does take place in the designated dump site. As a matter of interest, the Coast Guard vessel will probably not have a more sophisticated navigation capability than the hopper dredge, with the exception that in some areas a Loran C receiver may be available.

119. Until this point in the dredge and dump cycle, the factors affecting the operation are independent of whether the material is to be dumped in a borrow pit or simply dumped in open water.

Navigation in the Borrow Pit Area

120. Navigation requirements in the borrow pit area are much more stringent than those required in the first stage and are intimately related to the type of material to be dumped and the size of the borrow pit. As indicated in an earlier section, existing borrow pits range from 1 to 30 acres and tend to be circular or rectangular. Assuming that they are circular, the pit radius for different area pits is shown in the following tabulation. If the dump vessel is to position itself near the

Acres	Radius, ft
1	118
4	236
10	376
16	473
25	590
30	647

center of the pit a navigation capability of approximately $\pm$ 100 ft will be required except for the 1-acre pit, which will require better accuracy. To put the problem in perspective, the ESSAYONS hopper dredge will approximately span a 5-acre circular borrow pit; thus the position of the hopper to be dumped, relative to the location of the radar antenna, must be known and corrected for.

121. The simplest way to achieve the required accuracy with existing equipment is to install a buoy in the center of the borrow pit. Using radar or Loran A, the ship approaches to within a nautical mile of the borrow pit and then switches the

radar to a local scale and searches for the buoy. The buoy will require a light and radar reflector; in areas where there may be substantial radar sea returns from wave facets, a radar transponder will probably be required.

122. Precision navigation will be required to implant the buoy in the proper place unless it is done during the time when the borrow pit is being formed by the sand-mining operation. Another approach would be to put out several buoys, with proper coding, and use these to guide the ship to the center of the borrow pit. Even the simplest of buoys, installed in open water and instrumented so that it is not a hazard to navigation, will probably cost $5000 or more. In addition, the cost of locating it relative to the pit itself must be included.

123. The ship's fathometer may also aid in locating the borrow pit if a detailed bottom is available. However, pit walls, having slopes of 1:8 or less, will not be easy to localize using the broad beam fathometers typically found on hopper dredges and tug boats. A readily available navigation method involves temporary systems such as Raydist which is used for offshore survey work. Temporary systems have the required accuracy and may be installed easily. However, a simple buoy would still be highly desirable since the Captain must maintain station, as well as locate the desired dump point, and this is much more easily done using a visual aid rather than a radio aid.

124. Thus, it is within the state of the art for a hopper dredge, or a tug boat, to transit to the borrow pit and locate itself on the surface within a circle enclosing the pit, provided that it is several acres in size. To accomplish this will require at least that a buoy be installed and surveyed and, most probably, the use of a navigation service such a Raydist.

125. The next requirement is position keeping relative to the borrow pit. In the section on disposal equipment, it was

estimated that it takes approximately 5 min to empty a hopper when it is filled with mud and silt. This means that the vessel must hold position relative to the borrow pit for up to 5 min to ensure that all of the material is dumped over the pit. After completion of the dump of a hopper, the vessel can either maneuver back into position to dump another hopper or simply dump hopper after hopper if the vessel is successfully maintaining position. The dump may require that the vessel maintain its position for a total of 20 min. With a hopper dredge using a Raydist (or equivalent) navigation system, a surface buoy, and the ship's Doppler sonar, this 20-min interval is well within the position-keeping capability of the vessel unless high winds and seas are present.

126. When dumping from a scow or barge, the situation is quite different. The navigation equipment may be located hundreds or thousands of feet away from the barge. When the dump is imminent, the tug and barge will be moving at a slow speed and the maneuvering ability of the combination will be minimal. Since the tug captain has almost no communications capability with the bargeman, it will be almost impossible to maneuver a barge consistently to within 100 ft of the predetermined dump site and hold it there until the dump is complete. There are several changes in operational procedure that could be implemented, such as shortening the tow line once the site is reached and using portable two-way radios between the barge and the tug. Shortening the tow line cannot be implemented if several barges are being towed. In Long Island Sound it has been demonstrated that if a buoy is installed at the desired dump point, a scow can dump directly alongside the buoy in good weather conditions.

127. Based upon the considerations above, it is concluded that:

a. Hopper dredges can fix their position near open-water borrow pits to approximately $\pm$ 0.25 nautical miles using navigation aids such as light towers or light ships and then running a fixed course at a known speed. If these navigation aids are not present, the fix capability is determined by Loran A and is approximately $\pm$ 1 nautical mile.

b. Tugboats equipped for ocean navigation have a similar navigation capability except that they do not have Doppler sonar so their fix accuracy is affected by how well they know their vessel speed and the local current conditions. Under ideal conditions they may approach an accuracy of $\pm$ 0.25 nautical miles using radar measurement from a known object, but more typically, the fix accuracy will be established using Loran A and will be $\pm$ 1 nautical mile.

c. Both hopper dredges and tugboats require aid in identifying their position relative to the center of the borrow pit. With a navigation service such as Raydist, they should be able to return consistently to $\pm$ 100 ft from the center of the borrow pit once its coordinates have been established. An alternate method consists of a buoy and radar transponder to mark the center of the pit. Even with a supplementary navigation system, a simple buoy is recommended as a visual aid to assist the Captain in holding position relative to the pit.

d. It is feasible to maneuver and to hold a hopper dredge in position even while dumping in small borrow pits (several acres), provided that a buoy and/or enhanced navigation services are provided.

e. It is feasible only under ideal conditions to maneuver and hold position with a tug barge while borrow pit dumping. Since the tug has virtually no station-keeping control over the barge once it reaches the dump point, wind and current must be low enough to allow the barge to stay on station for the entire time of the dump once it is initiated, or multiple approaches to the site must be made. Dumping will require a buoy so that the bargeman can determine when to initiate dumping. Even under the best conditions, it is not likely that a tow longer than two barges can be effectively maneuvered into position over a borrow pit unless it is very large.

Short-Term Behavior Of Material During Dump

128. In the first two sections of this part, it was established that the hopper dredge, and in some cases a barge, could be maneuvered and held in position over the dump site with a fix accuracy of $\pm$ 100 ft. This section addresses the behavior of the material from the moment that it leaves the dump vessel until it either comes to rest upon the ocean floor or is swept out of the area by ocean currents.

Descent Phase

129. The following intuitive picture emerges from consideration of the descent phase. At the moment that the hopper or barge doors are opened, the material has zero vertical velocity. The doors open and the material drops out of the bin driven by its excess density relative to the surrounding water. Initially, the material behaves as a single mass and accelerates rapidly, approaching a terminal velocity determined by its density, size, and shape. While it is falling, the cloud is entraining water at its face and growing in size, thus decreasing in density, and the cloud begins to slow down. This phase is critical in establishing the behavior of the material once it reaches the bottom because the impact velocity may be closely related to the spreading of the material and the formation of a turbidity cloud.

130. Three methods are currently available to assist in determining the behavior of the material in the descent phase: Koh-Chang model predictions,[29] Krishnappan model predictions,[30]

and the results of field studies by Gordon[11,12] and Sustar.[13*] As shown in Appendix A, the Koh-Chang model was run for a number of different conditions to examine the sensitivity of the output to changes in the input parameters. For example, Figure 4 shows the effect of dump volume on the Koh-Chang prediction of descent velocity for a 50-ft water depth.

131. Figure 5 shows the predicted vertical descent velocity as a function of water depth using the Krishnappan model and two examples taken from his report. These predictions are for dumps with initial radii of 3.3 and 6.6 ft. A third prediction is also shown for the same initial conditions but scaled up to a dump volume of about 300 cu yd. When the latter curve is compared to the Koh Chang predictions, reasonable agreement is seen. Field data provided by Gordon, however, indicate descent velocities that are considerably lower. Krishnappan's model for descent velocity does not include the initial velocity and the buildup to terminal velocity. Thus, the prediction cannot be valid near the beginning of the descent phase and his simple model requires modification to adequately represent this part of the dump. The dashed lines in Figure 5 represent extrapolation of model predictions to conditions nearer the water surface.

132. The relative agreement between Koh-Chang and Krishnappan predictions of a high descent velocity are in disagreement with the data provided by Gordon. This uncertainty in descent velocity cannot be resolved without additional measurements.

133. Figure 6 shows the predicted cloud size during the descent phase for both the Koh-Chang and Krishnappan models. In each case it was assumed that the initial radius was 20 ft and the entrainment coefficient α was 0.25. The predicted cloud

*The following discussions of the short-term behavior are based on the cited references; no further citations will be given.

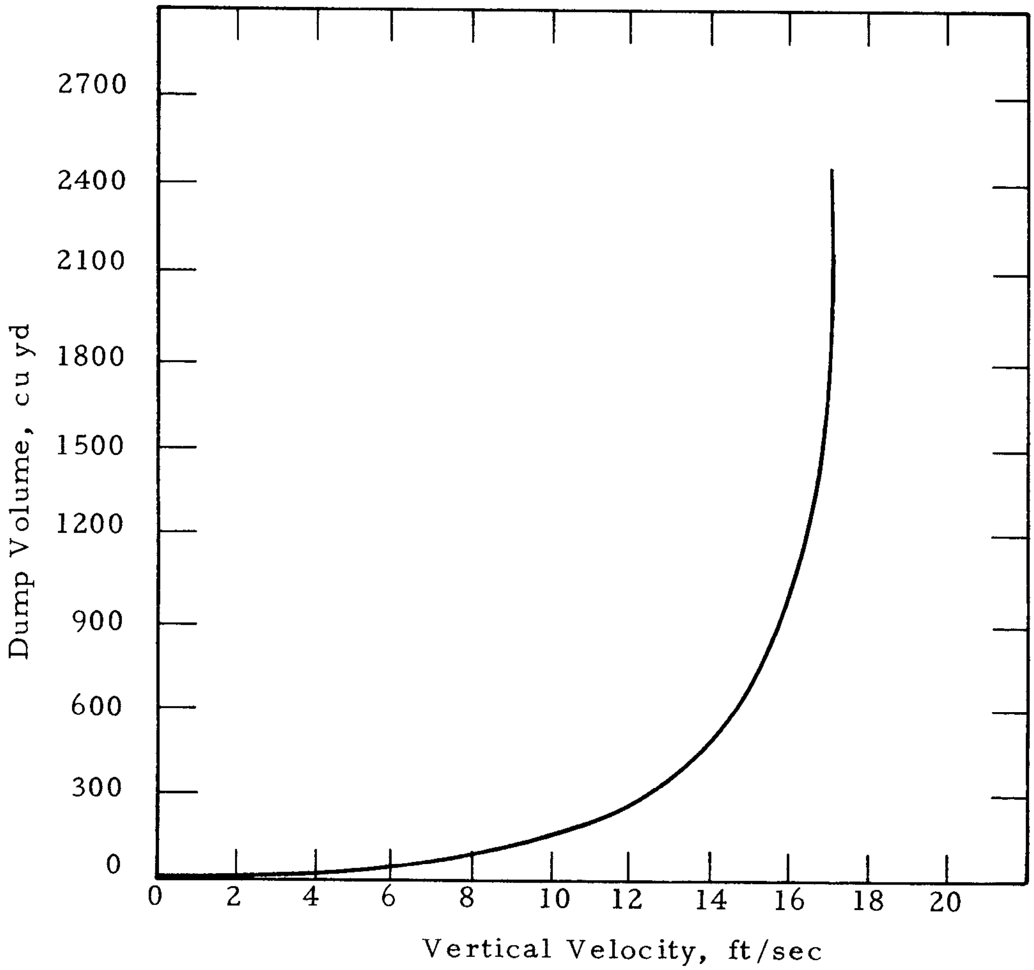


Figure 4. Koh-Chang predicted maximum vertical descent velocity as a function of dump volume (water depth = 50 ft)

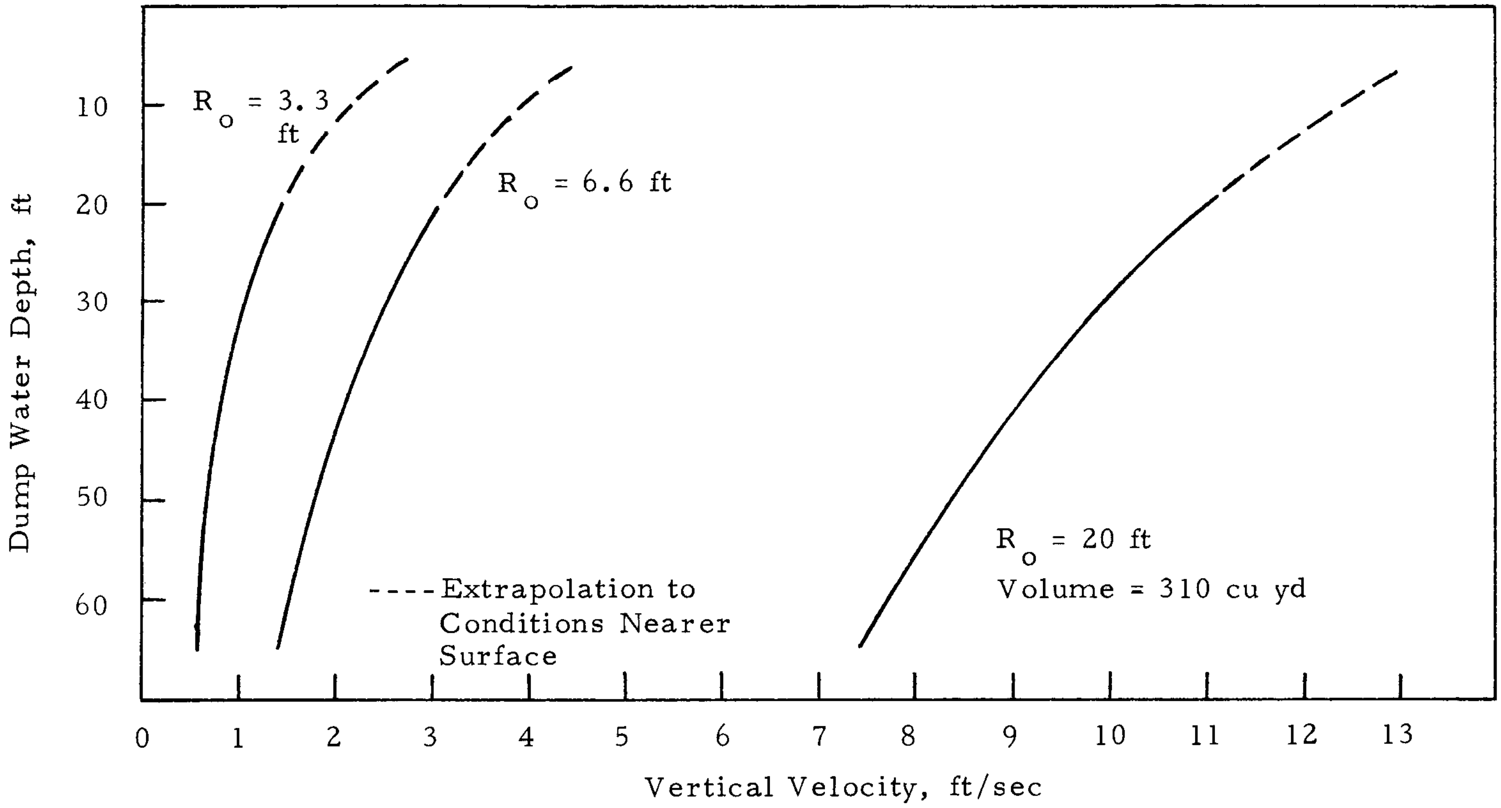


Figure 5. Vertical descent velocity as a function of dump initial radius (R_o) as predicted by the Krishnappan model

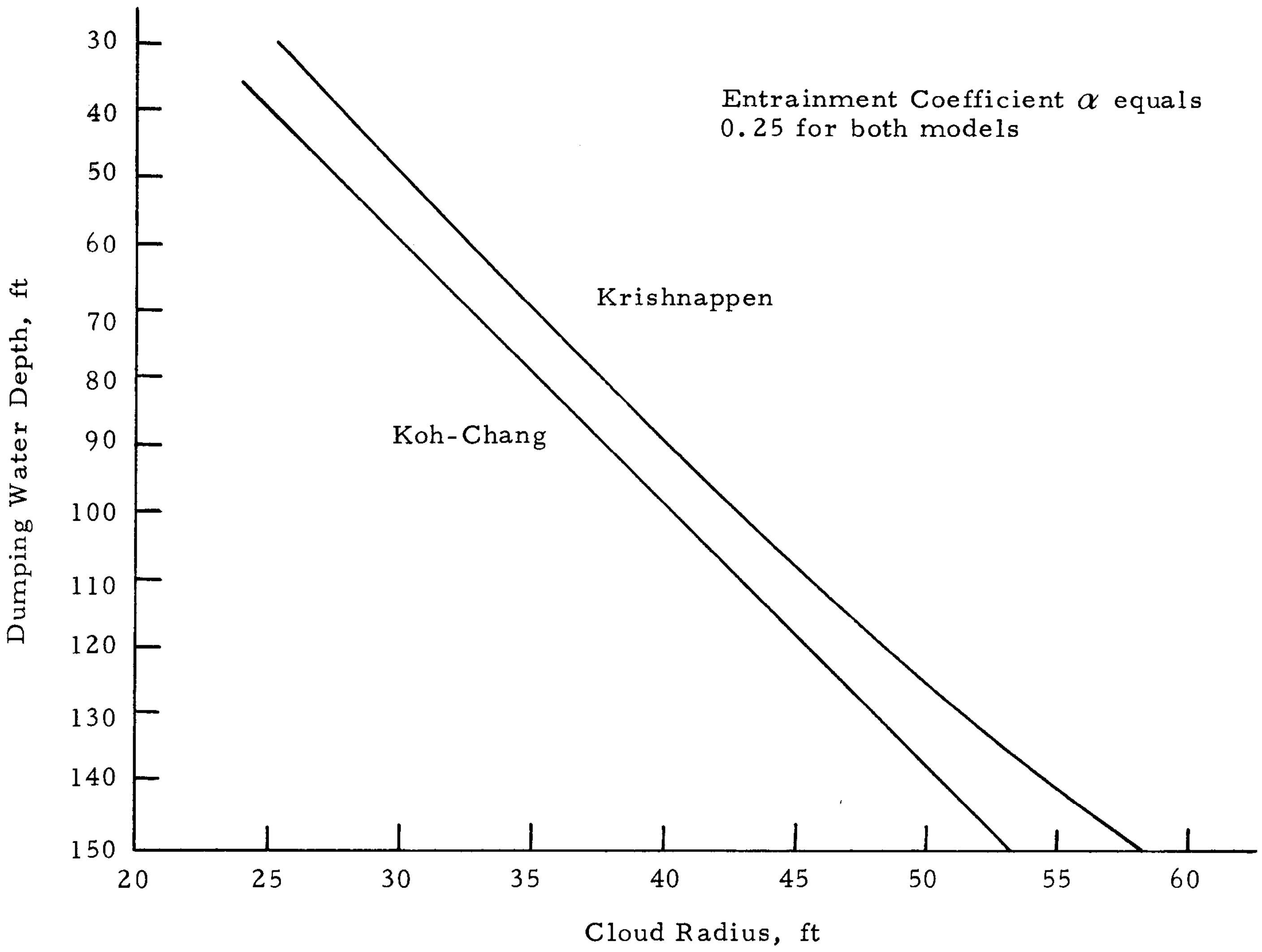


Figure 6. Predicted cloud radius as a function of water depth

sizes are seen to be quite similar.

134. At this time, based upon the scant amount of field data available, the correctness or incorrectness of either model cannot be established. However, the Koh-Chang and Krishnappan models both predict that the descent velocity should be substantially larger than that observed in Gordon's two field data points. The physical mechanisms at work during the descent phase are not completely understood, and additional laboratory and field studies are necessary before the uncertainty associated with critical parameters such as impact velocity can be resolved.

135. One additional consideration is the effect of ambient water density changes with depth on the descending cloud. The Koh-Chang sensitivity analysis indicates that, for every case examined, the cloud does not stop at an intermediate depth, but rather, impacts on the bottom. The opposite may occur with low density sludges or in deep water. The models allow particles to drop out of the cloud as soon as the main cloud descent velocity falls below the individual particle-settling velocity. Thus, large particles would fall out and the main cloud would continue to entrain water and slow down, losing fractions as their individual particle-settling velocities meet the above criterion. Krishnappan indicates that for the depths of interest to this study (150 ft or less) the descending cloud never decreases to a velocity low enough to allow separation to occur. Based upon the Koh-Chang predictions, Krishnappan predictions, and observed field data it appears as though for dumping in waters to depths of approximately 150 ft, the ambient water density gradient may be ignored with regard to collapse of the cloud and that the cloud will reach the bottom.

136. Neither the Koh-Chang nor the Krishnappan models make provisions for generating a turbidity cloud by material being ejected from the main cloud as it descends. The dump

process and eddying in the vicinity of the descending cloud undoubtedly spin off material since turbidity has been observed immediately after the dump phase. Gordon estimates this turbidity cloud to contain less than 1 percent of the dumped material. However, virtually nothing is known of the mechanisms that generate this turbidity cloud and their relative magnitudes or of the behavior of the turbidity cloud itself. Johanson[31] reported on measurements of the turbidity generated by a hopper dredge overflow and found that the turbidity cloud behaved as would be expected from individual particle-settling characteristics. Figure 7 shows the percent light transmittance in the turbidity cloud as a function of time for two different depths. The material was discharged 2 ft below the surface. During the first few minutes, sand and silt particles were settling out. The fine silt and clay particles remained in a layer near the surface and the concentration slowly approached background, due primarily to horizontal dispersion.

137. Thus it would be expected that the turbidity cloud generated by the dumping operation would remain in the dump area a considerable length of time unless a current were present. It would diffuse vertically and horizontally, slowly settling to the bottom. Since settling velocities for silt and clay are very low, the finest material from the turbidity plume might be swept out of the area or collapse on a density layer and never reach the bottom in the dump site.

138. Currents in the dump site most probably have a negligible effect on the main cloud. Both the Koh-Chang and Krishnappan models predict a large descent velocity. Gordon and Sustar both established that the material appears to descend vertically to a spot under the dredge. Even if Gordon's data are correct and the so-called "average velocity" is

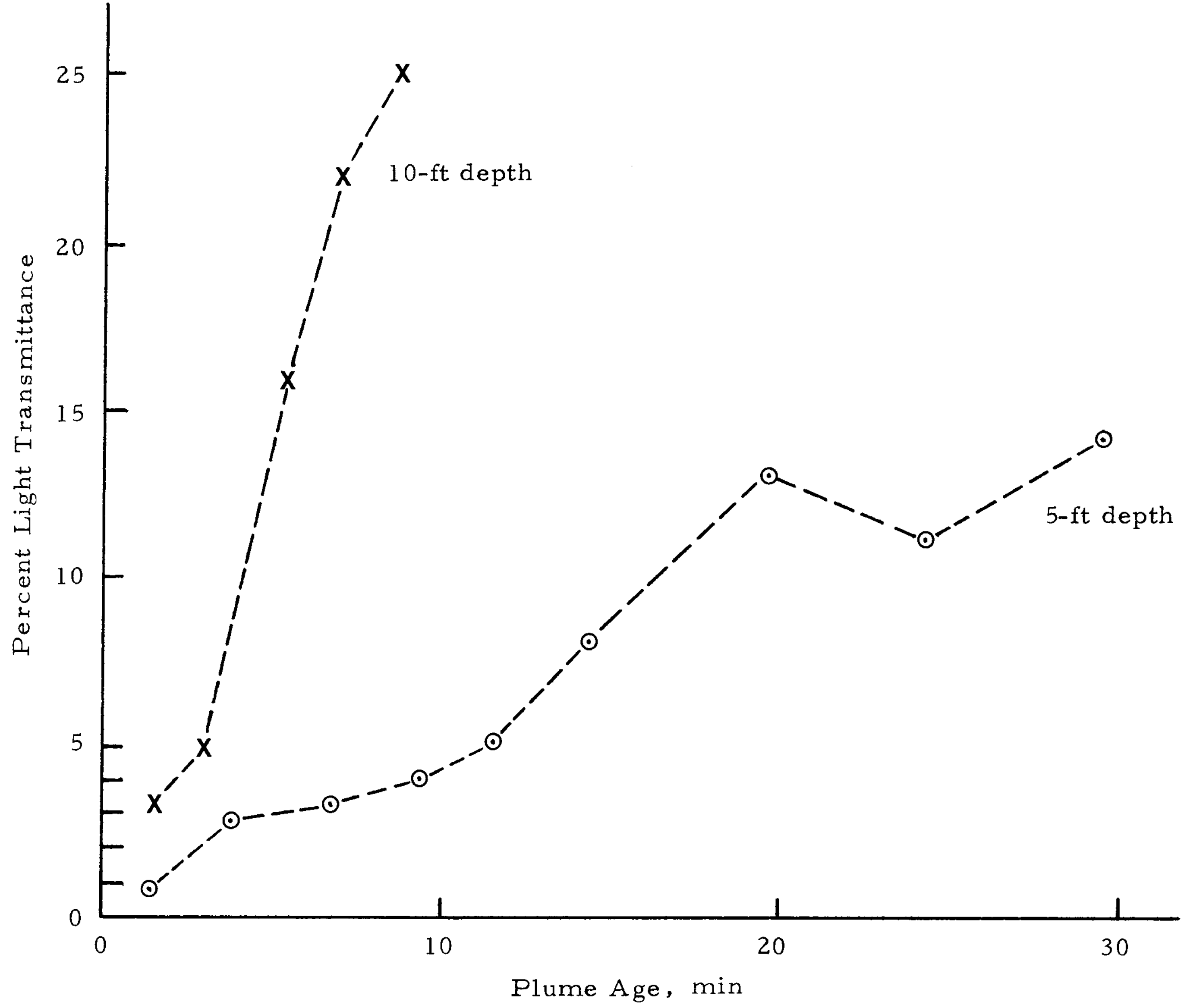


Figure 7. Plume age vs percent transmittance

approximately 2 ft/sec, the velocity near the surface is undoubtedly much higher initially.

Collapse Phase

139. The collapse phase covers the period of time from the moment that the main cloud reaches the bottom until all of the material has collapsed on the bottom or moved out of the area of interest. Since the main cloud vertical descent velocity, for cases of interest here, appears to never reach zero until the material hits the bottom, that is the only situation that will be considered.

140. Collapse involves several actions. The material from the main cloud impacts on the bottom, probably causing some resuspension of the surface material present before the dump. The material dumped then mounds or moves horizontally in a density layer flow, or both. Undoubtedly a local turbidity cloud is also formed.

141. The Koh-Chang model predicts a statistical measure of the horizontal extent of the material on the bottom at the end of the collapse phase. This measure is the standard deviation σ. If a distribution is assumed for the material σ can be interpreted as the distance within which a known percentage of material has been deposited. In Appendix A, the σ and height at the center of the distribution are presented assuming a normal distribution for height calculations shown graphically in Figure 8. Also shown are the predicted values as a function of dump volume for a dump depth of 50 ft. Note that a dump depth of 50 ft does not mean 50 ft of total water depth, but rather 50 ft of water below the lowest point in the barge or hopper bin.

142. The ratio of collapse size σ to cloud radius at the moment of impact is shown in the following tabulation:

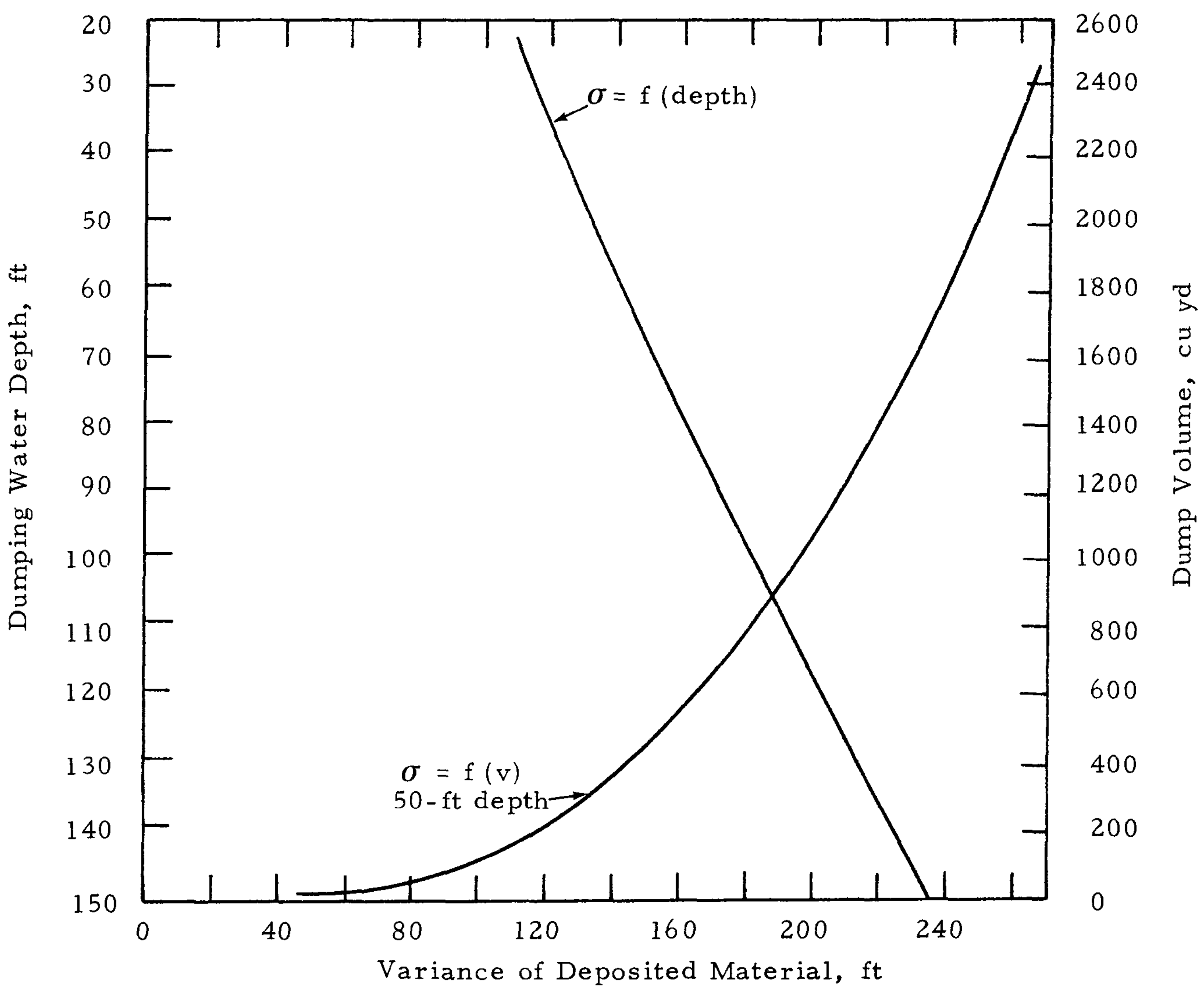


Figure 8. Collapse size σ as a function of water depth and dump volume

Water Depth	Cloud Radius	Collapse Size σ, ft	σ/Radius Cloud
25	24	108	4.5
50	29	137	4.7
100	41	186	4.5
150	53	238.5	4.5

The interesting point is that the predicted ratio appears to be constant as a function of depth for the material input used. Table A-5 in Appendix A indicates only slight variations in σ as a function of solids density or particle fall velocity. Thus, this relation does not appear to be sensitive to material type. It is premature to draw any firm conclusions, but if the Koh-Chang model predicts that the dynamic collapse σ is a constant times the cloud radius, it may be possible to simplify the model significantly for modelling heavy dumps in shallow water. Furthermore, since the Krishnappan model predicts very similar cloud radii to the Koh-Chang, it might be possible to predict equally valid (or perhaps nonvalid) dispersion (descent and collapse radii) using the Krishnappan model and a slide rule instead of the Koh-Chang and a CDC 6600 computer, once the constant σ/cloud radius is established. There are many cases, however, that the Krishnappan model does not cover (initial velocity greater than zero, pump out, discharge in the wake, etc.), and these are addressed by the Koh-Chang model. The sensitivity analysis of the Koh-Chang model, presented in Appendix A, demonstrates that some parts may be overly complicated, although the model as a whole is easy to use.

143. Gordon's data from Long Island Sound provides two field data points that can be compared to the Koh-Chang predictions. A number of scow dumps were made with material whose composition varied from 42 to 60 percent water and with typical fractions of about 20 percent sand and 80 percent silt

and clay. He estimated, based on turbidity and bathymetric measurements, that 80 percent of the material remained within a circle of radius 100 ft and 90 percent within 400 ft. These data points do not appear to fall on a normal distribution. However, if it is assumed that the 80-percent measurement does fall on a normal distribution, its σ would correspond to a radius of 78 ft. Similarly, assuming that the 90 percent measurement falls on normal distribution, its σ would be 243 ft.

144. A second reference point can be obtained from Sustar's dumping experience with San Francisco Bay sediments.* While little data have been released at this time, the following description can be made from a verbal communication. Using a barge, a dump of bay sediments was made in 100 fathoms (600 ft) of water. Prior to dumping, the U.S. Navy CURV unmanned vehicle scraped a rectangular grid measuring approximately 1000 ft by 500 ft into the bottom sediments. The dump took place while the barge was transiting on a course down the center of the grid. Indications from photos made by the CURV some time after the dump are that the material did not spread beyond the 500-ft grid lines. However, immediately after the dump, divers determined that the material had a horizontal displacement of 100 ft and 1700 ft. The 1700-ft dimension is probably related to the velocity of the barge during the dump which at 4 knots corresponds to a distance traveled of 2500 ft. It appears as though the material did not spread significantly after hitting the bottom, perhaps only 100 ft.

145. Snyder made side scan sonar measurements of dumps in Massachusetts Bay.** One record obtained during

*Personal Communication, March 1975, John Sustar, U.S. Army Corps of Engineers, San Francisco District, San Francisco, California.

**Personal Communication, December, 1974, Mr. Snyder, EG&G, Inc., Waltham, Massachusetts.

a dump showed the descent phase with little indication of a collapse phase. Other records taken over old dump sites showed what appeared to be discrete patches on the bottom around the general dump site, indicating little spreading after impact. It is possible, however, that the heavy material impacted and generated discrete mounds and that the light material remained in suspension and was transported out of the area by current.

146. Based upon the available field data and model predictions it is difficult to quantify the magnitude of the collapse phase. However, indications are that spreading from a barge or hopper bin dump is probably on the order of several times the radius of the cloud when it impacts on the bottom which most probably amounts to several hundred feet radius for the depths of interest. There have been no situations reported where the spreading from this mode of dumping caused a density layer flow that covered distances comparable to that seen in hydraulic pipeline dredges, but that is not to say that a density layer does not occur for this mode of dumping.

Diffusion Phase

147. A complete description of the short-term fate of the dredged material requires a consideration of the behavior of the turbidity cloud and the particles in the main cloud once the dynamic collapse phase has ended. It is possible that the collapse phase ends (no horizontal cloud velocity) leaving a turbid cloud of fine suspended material several feet from the bottom. This cloud may diffuse vertically and horizontally for which the Koh-Chang model makes predictions. A more important consideration would be dispersion due to the effects of water currents on this material. Based on the turbidity plume measurements reported on earlier, this material could take hours or days to settle to the bottom.

148. Figure 9 shows the distance that the suspended material would be transported as a function of time for two different water current velocities. It is readily apparent that fine silt and clay, having long settling times, will be swept out of the dump site area for even low values of bottom current. Material in the cloud would be transported 1000 ft in 10,000 sec with a bottom current of 0.1 ft/sec.

149. Predictions using the diffusion phase of the Koh-Chang model will not be discussed other than to say that the water current velocity input to the model is inadequate for most environments and that predictions of the long-term transport of material will require a three-dimensional, time-variable water current field.

150. The following conclusions can be drawn about the short-term behavior of material during the dump phase.

- a. There is substantial disagreement between the predicted descent velocity and the one set of field data available.
- b. Both the Koh-Chang and Krishnappan models predict similar descent velocities and main cloud radii.
- c. Field measurements and model predictions for water depths of interest both demonstrate that little spreading will occur once the material hits the bottom. Krishnappan predicts that the cloud will form a radius on the order of 40 to 50 ft and then will simply mound on the bottom. Koh-Chang predicts a similar cloud radius, but then predicts a 4.5:1 spreading due to the cloud collapsing on the bottom for a total bottom radius of 200 to 300 ft. Measurements by Gordon and Sustar indicated that most of the material remained within a 100-ft spreading dimension.
- d. Water current does not appear to substantially affect the main descending cloud but will most probably sweep any turbidity plume out of the dump site area due to the very low settling velocity of this material. There is reason to

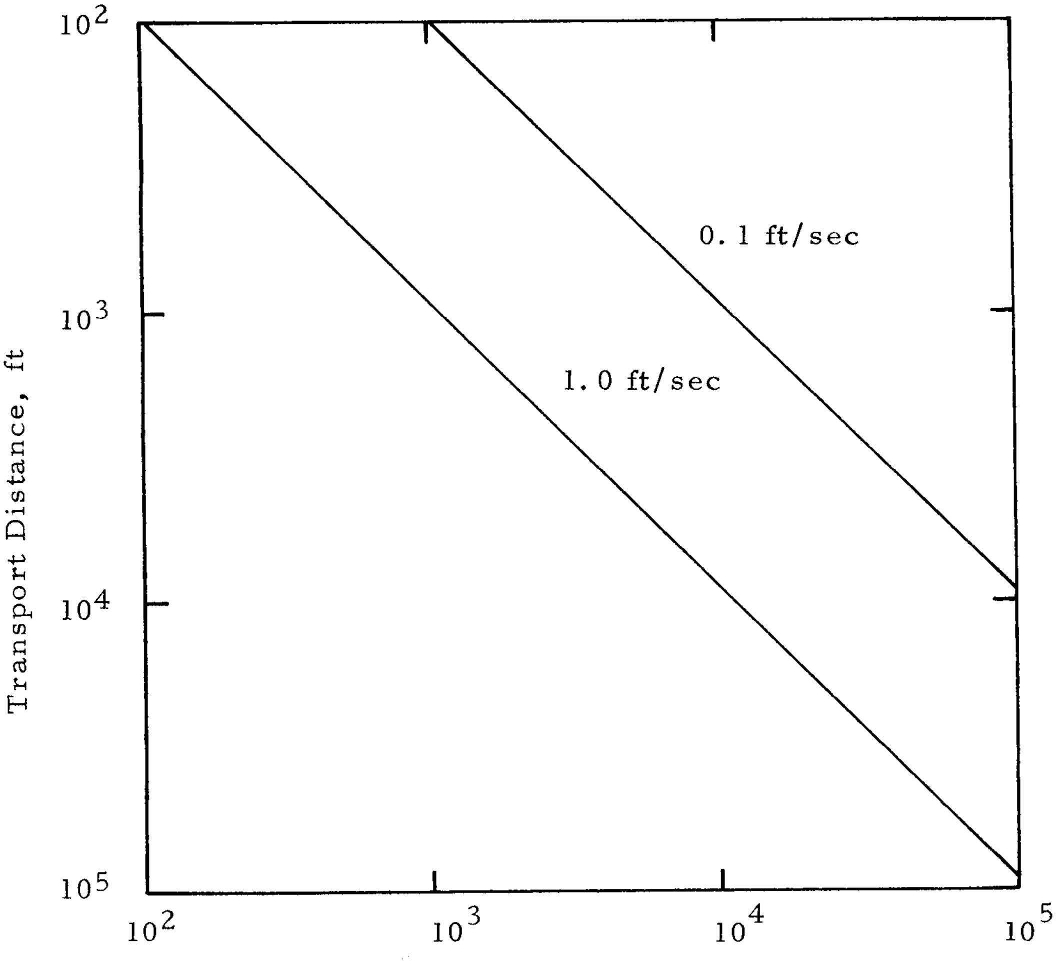


Figure 9. Particle transport distance versus time for two water current velocities.

believe that a turbidity cloud exists not only in the water column due to the initial dump and descent functions, but also on the bottom due to the impact and collapse phases.

e. Collapse phases and density layer flows have not been substantiated for bottom dumping operations, but it is likely that they exist under certain conditions.

f. The Koh-Chang model has been demonstrated, via a sensitivity analysis, to be far more complex than necessary for many of its predictions. The Krishnappan model is found to be too simplistic to handle some cases. Laboratory tests and controlled field tests are required before any substantial improvement in either model can be made with confidence.

g. Based on the field observations and the predictions of both models, it appears feasible to use a hopper dredge to place most of the material being dumped from the surface into a subqueous borrow pit of several acres size. The material that partitions into a turbidity cloud will most likely be transported out of the pit area, but this fraction has been demonstrated to be small for the dumps that have been studied. Gordon's estimate of less than 1 percent requires additional verification.

Long-Term Behavior of Material After Dump

151. This area of the study is perhaps the most difficult to quantify at this time. It will be assumed that the material being considered is claylike (cohesive) and probably polluted and that the pit is relatively large (a minimum of several acres). Thus the bottom currents are similar both in and adjacent to the pit. Finally, it will be assumed that the currents due to effects such as tides are low, or else the pit should not be considered acceptable for low-density material.

152. Once the material has been placed in a borrow pit, and has settled to the bottom, consolidation will begin and the ability of the material to be resuspended or eroded is time

dependent. While trends toward estimates of the time required for consolidation are known, quantitative prediction of the degree of consolidation as a function of time is generally not possible. The current velocity required to erode a given material is time dependent if the material is consolidated. The material may require days, weeks, or months to reach a high degree of resistance to erosion. Finally, little is known of the current structure in the open ocean just above the bottom, and less is known about the effects of borrow pits on this near-bottom velocity structure.

153. As discussed in Part II, the relevant considerations are to establish the time necessary to achieve a certain degree of consolidation for a specific sediment and then to determine whether storms or seasonal changes in the water current structure will cause erosion and resuspension.

154. The water motions that may cause erosion and resuspension are: intruding ocean currents, tidal currents, meteorological currents, density currents, river discharge currents, and storm-induced currents. With the exception of the latter, the magnitude of currents seen in open water should not be sufficient to erode silty sand and partially consolidated clays. Measurements and predictions of the bottom currents caused by storms indicate that these can be of sufficient magnitude to cause erosion. In some areas, the normal bottom current may not be sufficient to cause erosion, but once a storm has resuspended the material, the normal bottom current may sweep it out of the area.

155. The following can be concluded at this time:

a. The behavior of sediments after being dumped into the ocean and settling to the bottom is not clearly understood. The area of greatest uncertainty is the physical behavior of cohesive sediments.

b. It is not possible to estimate the water velocity necessary to resuspend or erode a cohesive material because the critical velocity will be a function of the consolidation of the material.

c. The long term fate of material dumped in subaqueous borrow pits cannot be completely established. However, it can be stated that borrow pits for disposal of dredged material should be selected in areas where the normal bottom current is low, perhaps 0.1 ft/sec or less. The dumping should take place at a time of the year to allow maximum time for consolidation before the storm season arrives.

PART IV: ALTERNATIVES TO EXTEND THE LIMITS OF FEASIBILITY

156. A number of alternative concepts have been identified as potential improvements for ocean dumping. Most of these concepts have been found to be inadequate, but several have warranted further consideration. These are described in this section and include the following:

- Pump down from hopper dredges
- Pump down from barges and scows
- Dredged material modifications
- Navigation

Pump Down From Hopper Dredges

157. The major limitation of all the dump vessels is that they cannot discharge the load at depths a few feet above the bottom where light materials would have a better chance of settling to the bottom before being transported by the current. The hopper dredge comes close to having this capability by virtue of its dragarms and pump-out system. The dragarms are mechanized and adjustable so that the draghead can be set for a 55- to 65-ft depth depending upon the particular dredge. The pump-out system incorporates the plumbing required to empty the hoppers using the dredge pumps. The modification discussed in this section would enable the dredge to pump out its load through the dragarm system.

158. The plumbing for the dredge pump system generally incorporates dual pumps whose suctions are connected to the two dragarms and the collection system. The discharge sides of the pumps connect to the hopper distribution system and the overboard discharge ports. The schematic, including the envelope lines for the pump room and the hoppers, is shown in Figure 10. The proposed flow path, shown by arrows in

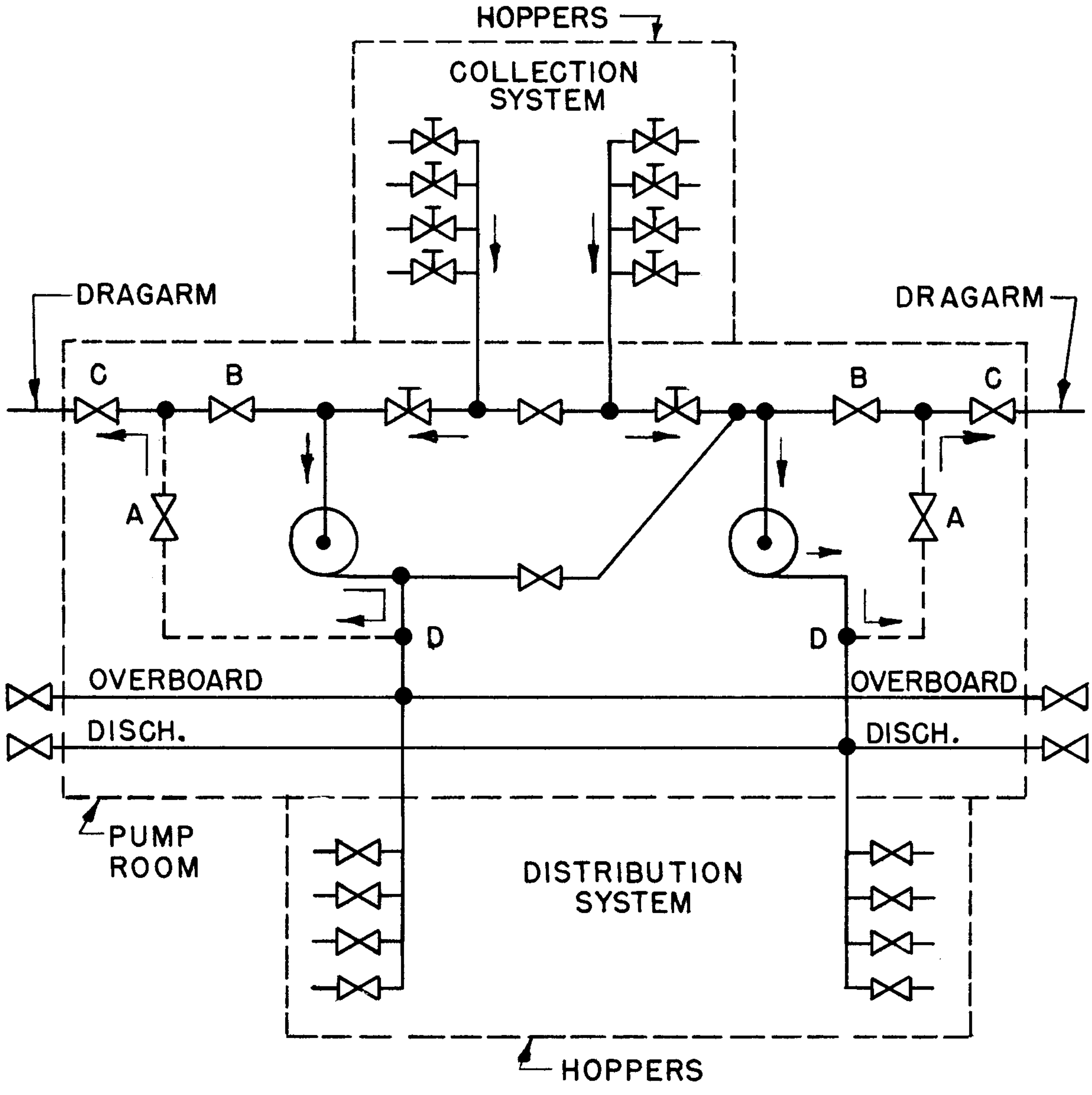


Figure 10. Dredge pumping schematic

Figure 10 is from the hoppers into the collection lines to the inlet of each pump. From the discharge side of the pumps, the flow must be routed to each dragarm port. This piping must be added to implement the concept and is shown by dashed lines in the schematic. The modification involves cutting into the main discharge lines at "D" with Y-branches and running full-size discharge pipe, with valves "A" installed, over to the dragarm ports. Y-branches must be added just inboard of the dragarm valves "C" between valves "C" and "B," and valve "B" must be connected into the system.

159. The preliminary cost estimate outlined below includes engineering and design labor, installation labor, and material costs and assumes that the installation would be performed during regular shipyard overhaul in order to avoid loss of operating time.

Engineering Design	$ 25,000
Materials	100,000
Installation	25,000
	$150,000

160. The pump-down operation is the same as that for pump out except that the dragarms are lowered before the dredge pumps are turned on, and the appropriate valves are set so the discharge flow is delivered to the drag ports. With due regard for the bottom contour the drag operator sets the draghead as close as he safely can to the bottom, preferably to within a few feet. The dredge pumps are then turned on and dredged material flows down the dragarm and is discharged through the draghead. Figure 11 shows the orientation of the drag system and the velocity vector relationships. In the absence of the debris grid, the discharge flow would jet out of the drag at angle Ψ_D, the depression angle of the dragarm. This is because the shell of the draghead does not obstruct the flow. The discharge velocity V_D is simply the velocity in the dragarm pipe. Due to the presence of the debris grids which act as turning vanes, the flow through the draghead is turned by the angle $\Delta\Psi$ so the

jet exits at an angle Φ_D, which is closer to the vertical, and at velocity V_D'. The velocity V_D' has a vertical component V_v' and a horizontal component V_H'. The vertical component V_v' is a measure of the impact energy, and the horizontal component V_H' is a measure of the transport energy of the jet. Under maximum flow conditions on the dredge GOETHALS, the discharge velocity V_D' was calculated to be 24 ft/sec.

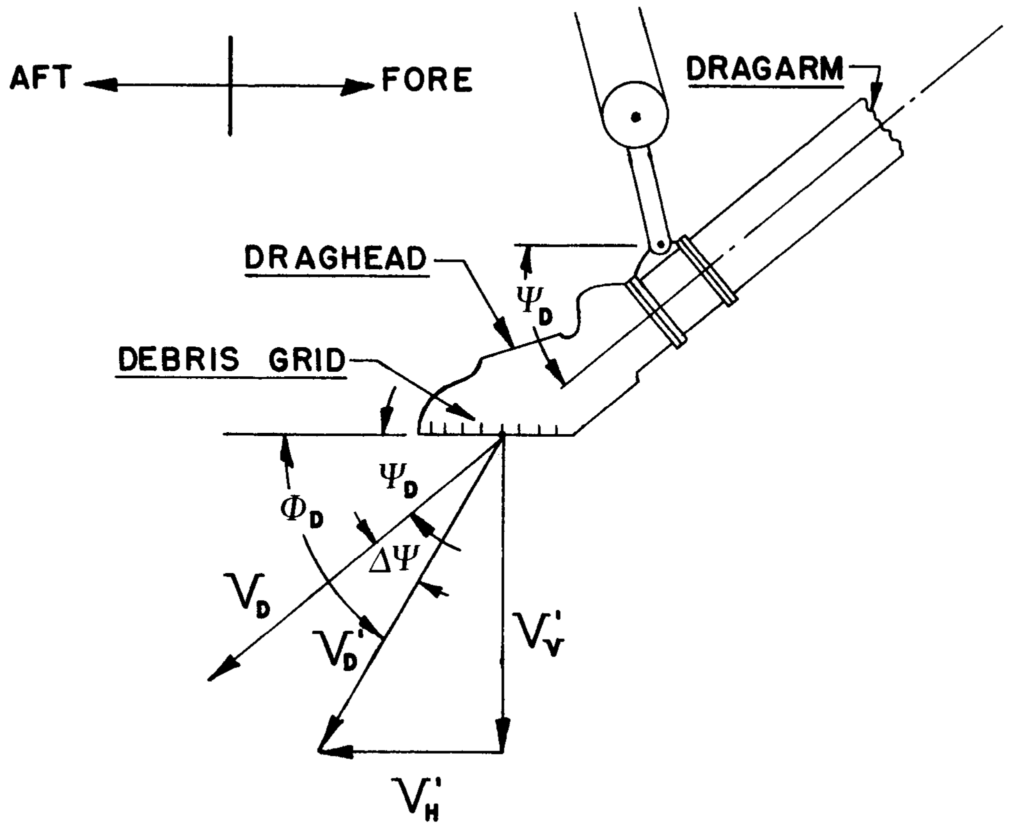


Figure 11. Draghead orientation and jet characteristics

161. Assuming the debris grids turn the flow halfway to the vertical and thereby reduce the jet velocity to 20 ft/sec and assuming the dragarm is set at 40 degs, the velocity components of the jet can be readily determined. The 40-deg angle is representative of the maximum depression angle and corresponds to a draghead depth of 55 to 65 ft. The component values for this case are as follows:

Pipe discharge velocity, ft/sec	24
Draghead discharge velocity, ft/sec	20
Draghead depression angle, deg	40
Jet depression angle, deg	65
Horizontal jet component, ft/sec	8.5
Vertical jet component, ft/sec	18.1

162. The vertical jet component V_v' at 18 ft/sec represents an extremely high impact energy level for a fine-grained dredged material. The jet would reach the bottom without appreciable diffusion or dilution. Impingement on the bottom would generate extremely active eddying and rapid diffusion in all directions including the vertical. Since the above velocity levels are representative of the maximum pumping rate, the pump down would require 15 min at the most. This is also the operating time for the discharge jet.

163. In the interest of reducing impact energy, the total velocity can be lowered to an acceptable level by reducing the delivery (RPM) of the dredge pump. Since an acceptable impact velocity might be any value below 3 ft/sec, the dredge pumps must be slowed to one-sixth of maximum delivery as given by the ratio of 3 to 18 ft/sec. This increases the pumping time from 15 min to 1-1/2 hr.

164. Examination of the velocity vectors of Figure 11 reveals a basic means of reducing the impact energy independent of pumping rate or time. Figure 11 represents conditions in still water with a stationary hopper dredge so that the vectors are a function only of the velocity in the discharge jet. If the vessel is given forward speed during the dumping operation, the horizontal component of the jet relative to the bottom and the stationary water is reduced by the ship's forward speed V_s. This is illustrated vectorially in Figure 12.

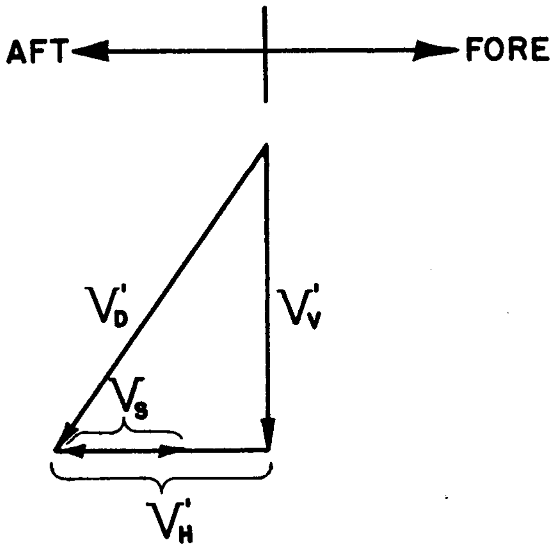


Figure 12. Discharge jet vectors

Particularly, if the ship's forward speed were set equal to the horizontal jet component ($V_s = V_H$, Figure 12), the dredged material would have no horizontal component and would move in a vertical direction at velocity V_v' ($V_D' = V_v'$) toward the bottom. The important fact is that the horizontal component of the jet can be reduced to zero by the ship's speed.

165. An additional consideration involves the direction of the discharge jet. Referring to Figure 11 the discharge flow exits from the dragarm at velocity V_D and depression angle Φ_D. If the flow is turned upward to the horizontal in the draghead, the total jet vector V_D', will be horizontal as shown in Figure 13. Now when the hopper dredge moves ahead at the same velocity as the jet, the dredged material is discharged at zero velocity relative to the water so that impact and transport energies are both zero. For the purposes of this report, this concept will be called horizontal pump down.

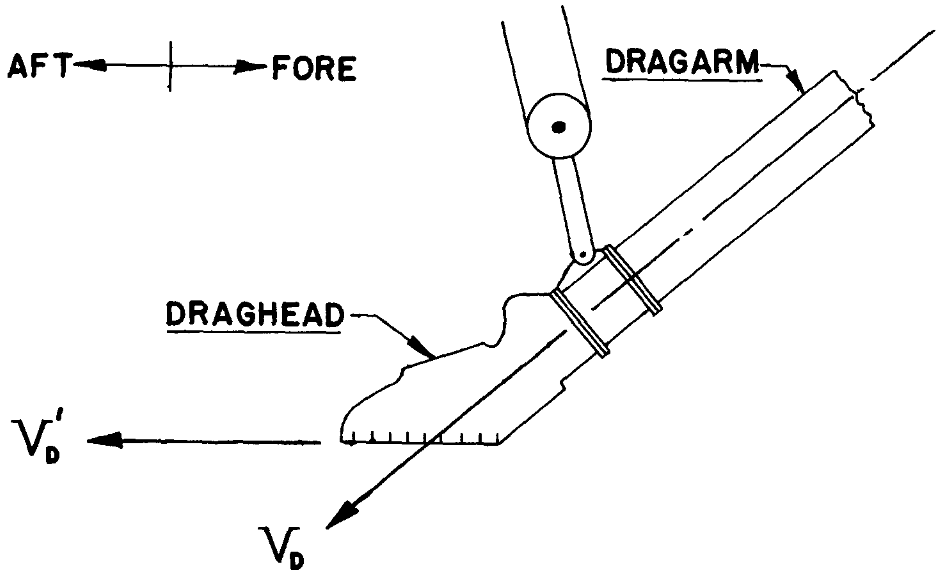


Figure 13. Proposed jet characteristics for pump down

166. Physically the two columns of materials laid down by the moving dredge remain stationary in the water if there is no current. As stated earlier it is desirable to discharge within a few feet of the bottom to ensure settling of the material before it is carried away. This may also place the draghead well within the bottom boundary layer in a region of generally quiet water so that current effects will be minimized. The draghead design must be altered so that the same head can be used for both dredging and dumping. Basically, the design must be capable of directing the dredge flow upward through the debris guard and into the dragarm while dredging, and during pump down, the flow enters the draghead from the dragarm and must be turned to the horizontal. These characteristics are shown in Figure 14.

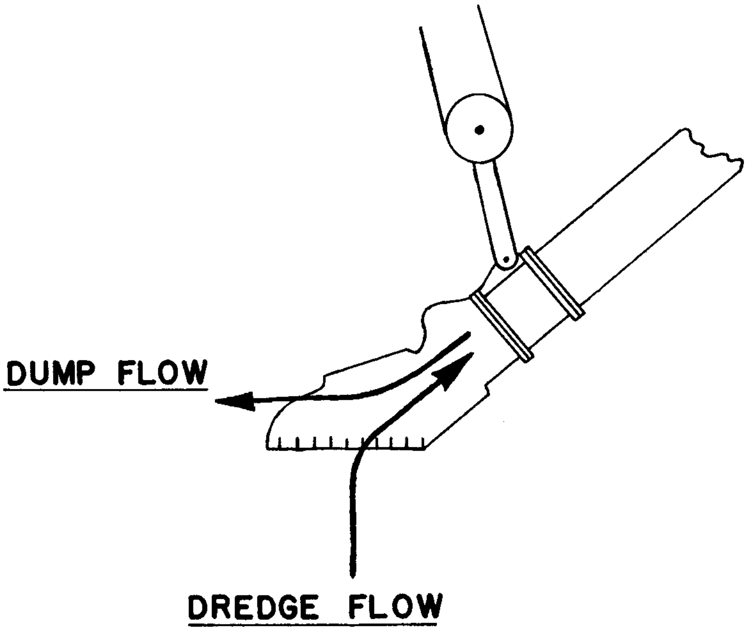


Figure 14. Proposed characteristics for combined dredge and pump-down draghead

167. The length of the dump track and the pumping time are determined from the equation for the total volume pumped. The volume relation is given by

$$Q = V'_D \; A_p t_p$$

where Q = Total volume pumped

V'_D = Flow velocity from draghead

A_p = Flow area from draghead

t_p = Pumping time

The total volume pumped Q is equal to the volume of the hopper load when the dredged material is mud and silt and flows satisfactorily without the help of jets or mixing water. If dilution is required, the hopper load volume must be adjusted by the mixing ratio in order to determine total volume pumped.

168. The area term A_p is the total flow area of all discharge jets that are operating. In the usual case of two operating drags, A_p would be the total flow area for the two discharge jets.

169. As can be seen from the above equation, once the pumping configuration is set and the mixing ratio established, the total volume pumped is constant and independent of V'_D and t_p. Indeed the product $V'_D t_p$ will be constant, which simply means that halving the pump rate requires twice the time.

170. When ship's speed V_s is set equal to the discharge velocity V_d, the product $V_s t_p$ remains constant for all combinations of pumping rate and time and also represents the total length of the dump track, since it is the product of the ship's speed and pump or dump time. In other words, one can select the ship's speed for the dump, adjust dredge pump rpm for the same discharge velocity, and perform the dump over the same track length regardless of the speed selection. The speed selection in turn determines the amount of time required to perform the dump.

171. As a numerical example, consider the dredge GOETHALS, which can empty its hoppers of a fluid and silt mixture in 10 min. Under these conditions the velocity of the flow through the dragarm is 24 ft/sec. Hence,

$$V'_{D\,max} = 24 \text{ ft/sec} = 14.2 \text{ knots}$$

$$t_{pmin} = 10 \text{ min}$$

and the length of the dump track S is given by their product.

$$S = V'_{Dmax} \times t_{pmin} = 14.2 \times \frac{10}{60} = 2.37 \text{ nautical miles } (2.72 \text{ miles})$$

172. It is not desirable to make the dump at top speed because the eddy action behind the dragarm will break up and disperse the discharge flow. From this standpoint a more reasonable speed would be 5 knots, especially since a longer pumping period is allowable. Hence, at $V_s = V'_D = 5$ knots and dredge pump delivery = 35 percent of maximum, the pumping time t_p would equal 28.4 min.

173. Assuming the borrow pit is long enough to make a pass of 1 nautical mile (NMi), the dump tract would appear as shown in Figure 15 below.

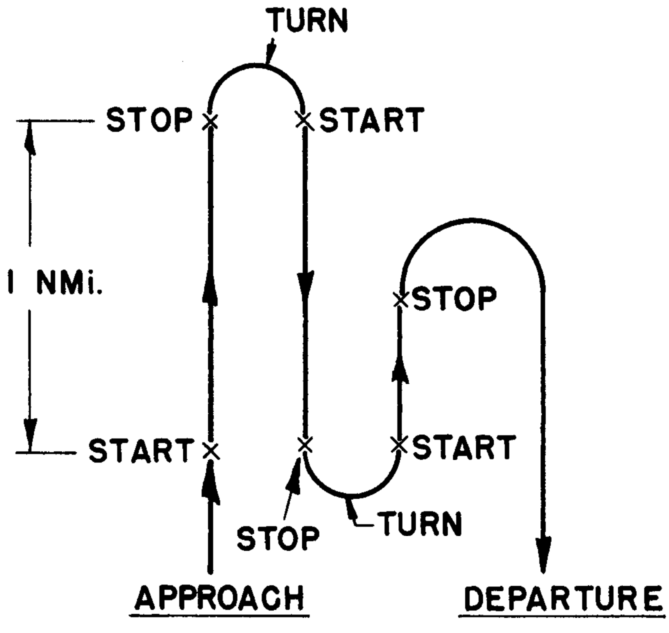


Figure 15. Typical dump pattern

The total time for the above pattern is comprised of 28.4 min pumping plus 5 min each for 3 turns, or 43.4 min for the total operation.

174. This horizontal pump-down technique uniquely meets the need to place the dredged material almost directly on the bottom with virtually no impact or dispersion. The approach may be used for borrow pit dumping but is equally valid for dumping on any other bottom, provided that the bottom roughness does not restrict lowering the draghead to the bottom. In many cases the draghead may be lowered all the way to the bottom and the material could actually be deposited within inches of the bottom.

175. Many exciting concepts suggest themselves, based upon this idea. For instance, since the material may in the form of a cloud almost directly on the bottom, artificial borrow pits could be generated by using buoyant silt curtains to form vertical walls around the disposal area or to simulate steep walls around old borrow pits. Future research will involve redesigning the draghead to minimize the distance from the bottom and any dispersion associated with the horizontal discharge, tests to establish the maximum allowable discharge velocity for a given material, and the development of instrumentation to monitor the discharge point and to determine the required vessel speed.

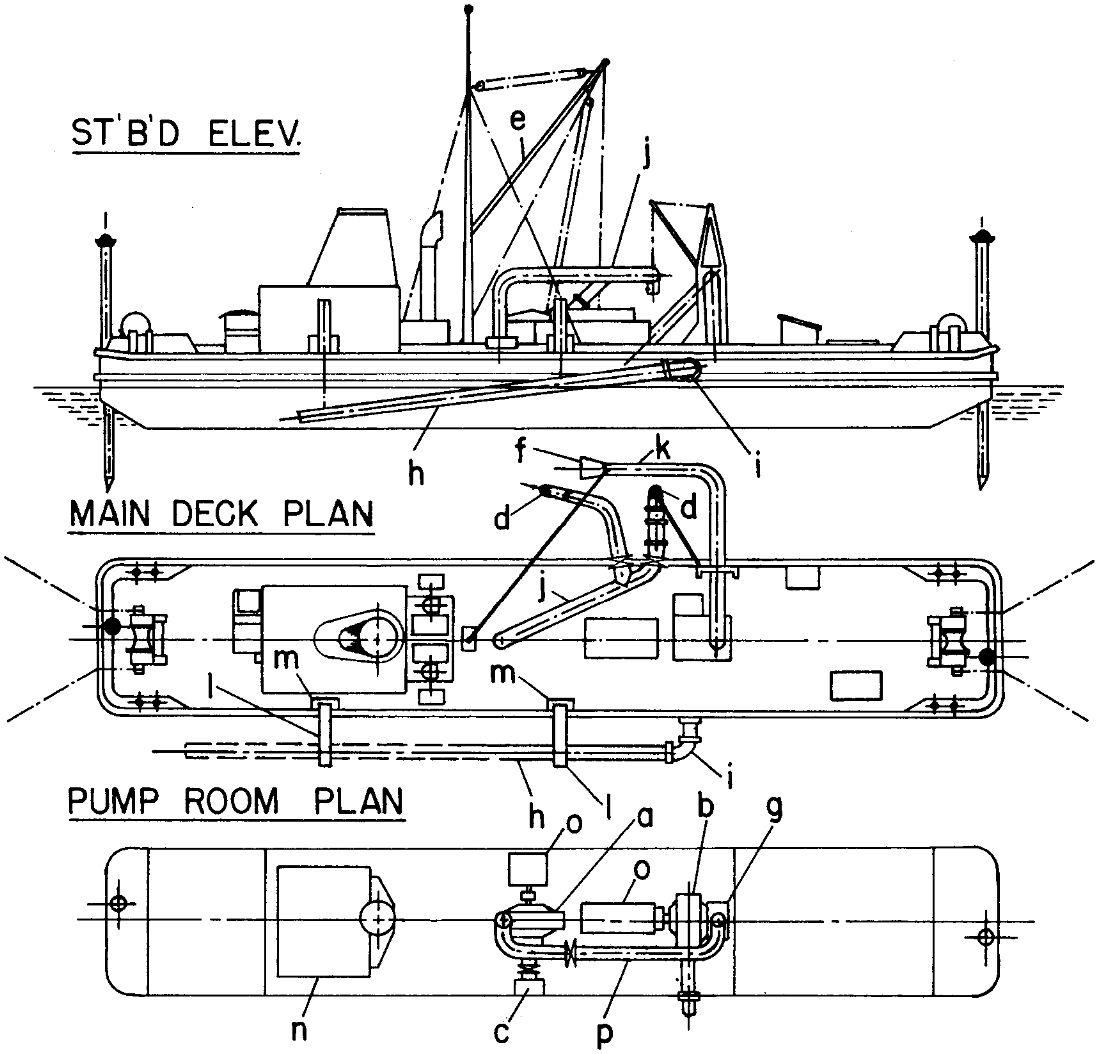
Pump Down for Barges and Scows

176. Barges and scows have limited use for borrow pit dumping because they cannot discharge close to the ocean bottom and have no inherent capability to be pumped out. These limitations can be overcome by introducing an unloading barge that dredges the material out of the scow and pumps it down a discharge pipe whose termination is set close to the ocean bottom. These vessels are commonplace in Europe where they are used to unload dredge barges and pump the dredged material ashore

via a pipeline. Figure 16 illustrates the typical features of an unloading barge. For use on the borrow pit dumping program, the unloading barge would be moored or spudded in place at the specific dump location in the pit area. Loaded barges and scows would tie up to it for the unloading operation. Equipment on the unloading barge would then be swung over the hopper of the scow and the load hydraulically dredged out. This discharge system is tailored for the borrow pit application and resembles the dragarm of a hopper dredge in that the free end can be lowered by winch to the desired discharge depth.

177. The unloading barge is equipped much like a hydraulic suction dredge except that the suction system is designed to pump out scows and barges. The system is organized around a jet spray pump and a dredge pump and includes all the associated plumbing and support structures. The jet spray pump is fed directly from a sea chest and supplies water to at least two spray nozzles that extend over the scow and are supported by cranes. The jet streams fluidize the material in the scow so that it can be drawn into the suction head. The jet nozzles are adjustable so that they can be aimed in the vicinity of the suction head. The dredge pump draws the fluidized mix through the suction pipe and past a stone chest to the inlet port of the pump. The pump discharges directly to a pump-down arm via an elbow immediately outboard of the hull. The elbow pivots at the hull connection and permits the discharge end of the arm to be rotated and set at a designated depth. The jet water lines and the suction pipe are each supported by cranes with some adjustability in their positioning. The pump-down arm is supported by davits and winches.

178. The power system for the unloading barge could be of many varieties. The early vessels were powered completely by steam and used separate steam drives for each powered component. Today it would be appropriate to use hydraulics



a.	jet spray pump	i.	pump-down elbow, pivoting hull
b.	dredge pump	j.	jet water lines
c.	sea chest	k.	suction pipe
d.	spray nozzles	l.	pump-down davits
e.	cranes	m.	pump-down winches
f.	suction head	n.	diesel power plant
g.	stone chest	o.	hydraulic motors
h.	pump-down arm	p.	priming pipe

Figure 16. Proposed pump-down barge

with main power provided by one or more diesel engines and each piece of equipment driven by a hydraulic motor.

179. The installation of the pump-out barge can be implemented in a variety of ways. The vessel could be secured on four mooring lines, even in the deepest water, in such a way that it can move itself along a dump track. An array of spuds in conjunction with a fore-aft mooring line can be manipulated to move the barge in a more positive manner. Operation depth is limited here by the maximum length of the spuds. When the vessel reaches the limit of travel on the mooring lines, the mooring blocks must be changed. The pump-down barge can be equipped with its own propulsion system thereby giving it the capability of moving itself from one anchorage to another within the borrow pits. The propulsion system can also be designed powerful enough to tow the scow with the help of its attendant so that the dump can be performed while underway.

180. Operations at the borrow pit dump site encompass docking, start-up, and pump-down procedures. Upon arrival at the dump site the tug maneuvers the scow alongside the pump-out barge under the array of spray nozzles and suction pipe. The scowman makes fast bow and stern lines. The arrangement is shown in Figure 17. The side tow is the most effective arrangement because the tug has more positive control and the problem of snagging towlines and mooring lines is minimized.

181. Following docking, the suction pipe and nozzles are moved into position and aligned and the pump-down arm lowered to the appropiate depth. Both pumps are located below the waterline so that they are primed and ready to start at all times. The jet water pump is turned on first after the valves are set to feed the nozzles. The load is fluidized and the suction head is positioned so that it is always submerged. The priming pipe

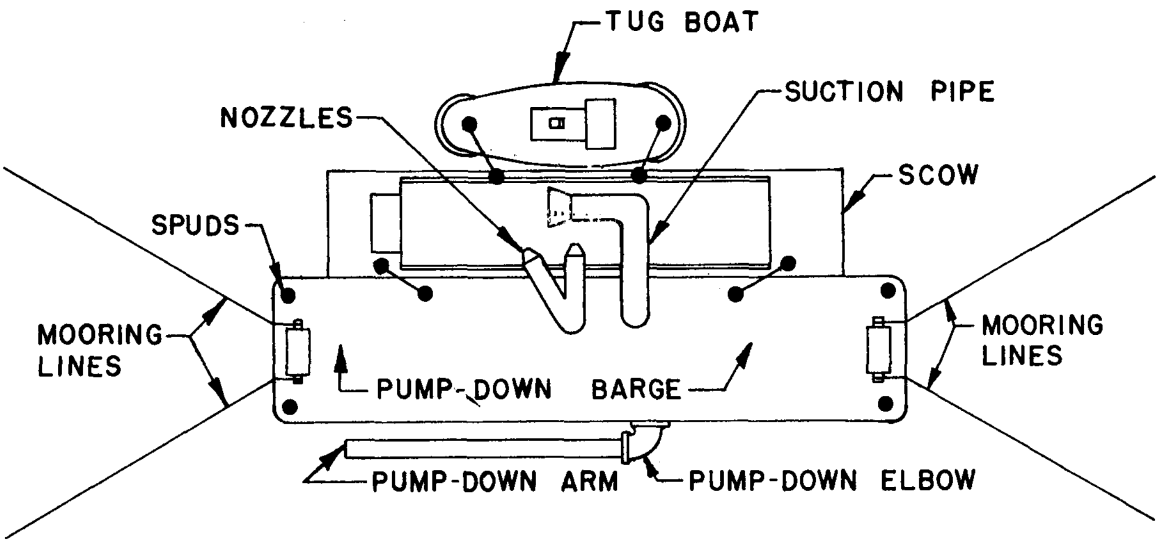


Figure 17. Docking arrangement for pump-down barge

is opened next to feed water to the inlet of the dredge pump from the discharge of the jet water pump. This water floods the pump and flows through the suction line, purging the line of air by forcing it out at the suction head. The dredge pump is then turned on; it draws dredged material from the scow and mixing water from the jet water pump, which is also supplying the jet nozzle. The mixing water can be adjusted down (to zero flow if necessary) for optimum pump-out rate from the scow. The priming operation is necessitated because the suction line is air bound at the start of each dump. The pipe rises vertically from the dredge pump and elbows across to the scow and down to the suction head. The height of the crossover pipe must be sufficient to clear the deck of the scow particularly in its lightened condition. The maximum height is limited by the static pressure in the crossover pipe. When the static pressure drops too low, the dredge pump delivery falls to zero.

182. During the pump-down phase, the handling of the suction system is critical to proper operation. The suction head must be submerged at all times to avoid indigestion of large slugs of air that cause the dredge pump to lose prime. The level of liquid in the scow must be watched closely and the suction head lowered (via winches) as the scow empties. In the case of a compacted load, the jet nozzles must be adjusted continuously to ensure proper fluidity at the suction head. If prime is lost in the dredge pump, it may be restored by opening up the mixing water line. If this fails, the dredge pump must be shut down and the priming procedure repeated. The suction head is also equipped with a debris guard that prevents excessively large stones and debris from being drawn into the system thus clogging the pump or causing mechanical damage.

183. The pump-down barge is capable of handling the range of materials from sand and gravel to silt and clay. The sandy materials are typically dry and compacted and require a great amount of dilution. This necessitates moving the suction head and nozzle array into the load as the material breaks down. The only practical way of doing this is to advance the scow gradually along the side of the pump-down barge. The fine materials, being quite smooth and fluid, will probably not require appreciable jetting. The dredged material dumped in borrow pits will likely be of this type. It is envisioned that the silt and clay mixture will be fluid enough to flow to the suction head so that the scow will not have to be moved during pump down.

184. The pumping capability of a medium-sized barge can be estimated by considering reasonable values for the physical parameters involved. Thus, for a 100- to 150-ft-long vessel, the largest practical piping system diameter is approximately 18 in. Systems larger than this become unwieldly. Looking ahead to the conditions at the discharge of the pump-down arm, the fluid velocity should be no greater than 3 ft/sec from a consideration

of the impact energy of the discharge jet on the bottom. The discharge flow can be easily diffused by a factor of 3 to 3.5 by effectively increasing the discharge area. If the discharge velocity is set at 3 ft/sec, the fluid velocity in the 18-in. pipe cannot exceed 10 ft/sec. This corresponds to a maximum pumping rate of 8000 gpm. Considering scows that are loaded with completely fluid mixtures, (i.e. require no jet fluidization) this system can pump down a vessel of 4000 cu yd in 100 min, 2000 cu yd in 50 min, and 1000 cu yd in 25 min. These times all represent reasonable operating conditions for borrow pit dumping.

185. The estimated cost of a pump-down barge 150 ft long by 30 ft wide is $3.5 million based on the cost of similar equipment in today's market. The economic burden of a new vessel can be lessened by modifying used equipment that is available. A hydraulic suction dredge is particularly attractive in this sense, since it comes equipped with a dredge pump system, crane facilities, and mooring equipment such as winches and spuds. The only major system to be added is the jet water system.

Dredged Material Modification

186. An approach to optimizing the placement of dredged materials in borrow pits would be to alter the characteristics of the dredged material itself to minimize dispersion during dumping, to prevent subsequent erosion, or both. To be considered as an option for modifying dredged materials, a process must appear to be practical and have a moderate cost compared to the overall disposal operation.

Reduction of Water Content

187. Reduction of the water content of dredged material would encourage the dredged material to sink rapidly and to spread across the ocean bottom as a density current, thus minimizing loss of solids from the descending cloud to the water column. At higher solids content the bottom density current

would be more strongly formed and probably have greater resistance to ambient currents. For cohesive materials at very low water content, the solids may settle as a cohesive mass and mound on the bottom directly below the dumping point.

188. Mechanical processes for the reduction of water content of dredged materials have been discussed by Johanson and Bowen.[32] Of the processes considered, the following conceivably could be applied to the reduction of water content of dredged material provided that power and operating space were available:

a. Gravity thickening. Thickeners use gravity to separate solids from water and operate as clarifiers but with a somewhat different design. The total capital and operating cost for a conventional thickener is between \$1.50 and \$5.00/ton of dry solids.

b. Flotation. Flotation employs fine bubbles that become associated with the solids and cause them to rise to the top of the tank where they are skimmed off. Operating costs alone are in the range of \$4 to \$5/ton of dry solids, and twice that if chemicals are required.

c. Vacuum filtration. Vacuum filtration would produce a dry filter cake, but a very large working area is required and the total for operating and capital costs is in the range of \$5 to \$30/ton of dry solids. Chemical conditioning costs may add another \$20/ton of dry solids.

d. Centrifugation. Centrifuges are generally effective, and cost approximately the same as vacuum filters.

189. It is clear that even the most simple scheme for mechanical dewatering of dredged material would very significantly increase the cost of the overall disposal operation. In addition, serious questions would have to be answered concerning process effectiveness on polluted dredged material, which, since they contain a large portion of fine-grained solids, would probably be

very difficult to dewater. Each of these potential processes would also necessitate large areas for setting up equipment. Thus, mechanical dewatering is not an attractive method for lowering the water content of dredged material prior to dumping in borrow pits.

Addition of Chemicals

190. Treatment of overflow water. Addition of chemicals to cause flocculation in barge compartments and hopper dredge bins would have several beneficial effects. It has been assumed that overflows during the dredging operation will not be allowed because the overflow water would contain an excessive concentration of fine material and possibly pollutants. If the fines could be captured and only clear water discharged, then more solids would be transported with each load. In addition to the benefits resulting from the larger loads, the increased solids content would allow placement of more material in a single dump, thus minimizing any inaccuracies in placement from multiple dumps. The solids also would have a considerably higher density, which would tend to ensure that the dump would rapidly reach the bottom and be less subject to dispersion. Even if overflows were still not allowed after chemical treatment, chemical addition would concentrate solids at the bottom of the hopper, or barge, and the resulting high density could lessen dispersion.

191. The concept of utilizing hopper dredge bins or scow compartments for gravitational settling of fine-grained sediments has been under consideration for a number of years. A 1969 study by the Philadelphia District of the Corps of Engineers[33] reported the results of field tests in which up to 10 hr of quiescent settling (without chemical addition in hopper dredge bins) failed to produce an effluent which could be discharged. Another study has been conducted by the Dow Chemical Company to investigate flocculant chemicals for treating hopper dredge

overflows.[34] It was concluded that it was not possible to settle out the solids within the hopper bin. Johanson and Bowen,[32] in a review of this work, considered that a hopper overflow chemical treatment system might be feasible if a two-step process were employed with plain sedimentation followed by chemical coagulation. A system using a combination of an inorganic salt (such as alum or an iron salt) together with an organic polymer, and under proper pH control, was suggested. The cost of such a system is difficult to estimate without further laboratory studies, but Johanson and Bowen estimated that for an overflow system with a flow rate of 10,000 gpm, the hourly chemical cost would be about $50. The cost of dredge modifications and other equipment requirements was not estimated, but would probably be significant.

192. Treatment of solids. It may be possible to treat the entire dredged material mass to improve its settling characteristics as well as to increase its ability to withstand long-term erosion. In a study by the New England Division of the Corps[35] to investigate methods for disposal of a highly organic sediment, consideration was given to incorporating more dense materials to promote sinking at an ocean disposal site. The materials to be added were soil at 20 percent by volume and two bags of Portland cement per cubic yard of dredged material to create a form of soil cement. The cost for materials and preparation of the mixture was estimated to be $3.22/yd of dredged material, compared to a dredging cost of $2.49/yd and a hauling cost of $2.00/yd.

193. In recent months two similar proprietary products have come on the market, which the manufacturers claim significantly alter the physical form of liquid sludges. Dravo Corporation has introduced a product called Calcilox H35, which is

said to stabilize wet sludges and improve dewatering characteristics.* Apparently the main application area is in the treatment of power-plant sulphur dioxide scrubber sludges, and although the chemical nature of Calcilox H35 has not been disclosed, it is made from a waste material and is available in large quantities. It is to be mixed in with the wet sludge in dry powder form at 2 to 4 percent. The result will depend on the dosage and type of waste material, but the mixture will set up in several days to several months. The pH of the mixture must be greater than 10 and may be controlled by adding lime. The chemical reactions that take place will occur either under water or in air. Thus, Calcilox H35 would not decrease dispersion during the dumping operation, but would prevent erosion and resuspension by providing a hard, or at least granular, surface. The chemical cost is in the range of \$30/ton, or approximately \$0.60 to \$1.20/ton of dredged material.

194. The second product for altering sludges is marketed by the Chemfix Corporation, a subsidiary of Environmental Sciences, Inc.** Selection of chemicals and dosing rate depend on the nature of the waste, the required speed of the reaction, and the end use of the material. Chemfix states that their product has been used in many industrial applications including several types of industrial waste liquids and sludges. The gelling agent is a soluble silicate with a setting agent and will set up under water, but more of the chemical (7 to 8 percent by weight) would be required than for air curing. Depending on the temperature, the initial set will occur in a few hours in warm temperatures and in up to 24 hr in cold conditions. Completion of the chemical reactions will take days to weeks and will produce a substance

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*Personal Communication, November 1974, Dravo Corp., Pittsburgh, Pa.

**Personal Communication, November 1974, Chemfix Div. of Environmental Sciences, Inc., Pittsburgh, Pa.

with the consistency of damp clay. No water is removed in the process and all water and heavy metals become entrapped in the solid end product. The cost for chemicals is about $0.02/gal with mixing and application approximately doubling that cost. In a large fixed-location operation, mixing and application might be 25 to 30 percent of the chemical cost rather than 100 percent for small mobile plants.

195. Either of these two chemical treatments might have application to the problem of placing dredged materials in borrow pits. The beneficial effect would be a reduction in the erodability of materials after placement. Laboratory, and possibly field studies, would have to be conducted to more precisely determine the benefits to be derived and the costs involved.

196. Immobilization of pollutants. Numerous chemicals are available that would act to prevent migration of pollutants from a dredged material deposit. These were not considered in this report since the contract scope of work statement excluded consideration of the environmental effects of borrow pits. These effects are being studied under other efforts also funded by the Dredged Material Research Program.

Encapsulation of Materials

197. Another dumping method that could be employed is encapsulation. The dredged material could be placed in containers, but the expense would be prohibitive. Another possibility is a lining for the hopper dredge bins or barge compartments. The objective would be to prevent entrainment of the material into the water column during the convective descent phase and, if the bag did not burst on impact, the collapse phase could be eliminated also. Problems associated with liners include adequate structural strength and the ultimate fate of the liner material. Strength problems would be most severe both on leaving the hopper bin or barge compartment and at impact on

the ocean floor. The doors of the compartments generally open to a maximum width of only about one-fourth of the beam dimension of the vessel, which would make it difficult for the bag to pass through the door without tearing. At this time encapsulation schemes do not appear practical.

Navigation

198. At the present time, navigation of bottom dumping vessels is provided primarily by radar fixes from known objects and Loran A fixes. Radar requires that fixed objects be located near the borrow pit and Loran A does not meet the navigational accuracy requirements of borrow pit dumping.

199. There are many acceptable ways to improve the navigational capability using systems described in Appendix B. Two clear choices are immediately available to meet the navigational needs for borrow pit dumping. The first of these, described in Appendix B, involves setting up a portable Loran D system to provide temporary navigation capability in the area while the borrow pit is being filled. This approach involves setting up the transmitters (which have been designed to be highly portable), generating a temporary Loran C navigation chart, and placing a relatively inexpensive ($3500-$4000) Loran C receiver on board the dump vessel. In the future, after the Coast Guard implements its United States Coastal Confluence Zone plan, there probably will not be a need to install temporary Loran D transmitters to cover a given location. Another equally acceptable approach involves the use of precision systems, such as Raydist, LORAC, and some of the Decca systems. These will provide a navigation capability equal to, or better than, Loran C and the systems are generally available on a rental basis.

200. Thus, navigation is not considered to be a problem with regard to borrow pit dumping, provided that the dump vessels

are instrumented with the correct receiver and the correct transmitters are installed on the shore adjacent to the borrow pit site.

PART V: METHODOLOGY FOR COVERING SUBAQUEOUS BORROW PITS

General Considerations

201. Situations may exist where it is desirable to apply a cover over the dredged material after it is dumped into the borrow pit. Two reasons for covering would be to reduce the availability of pollutants to the surrounding environment, or to reduce the tendency for erosion of deposited sediments.

202. Early work on the covering of polluted sediments was conducted in Sweden. Jernelöv[36] and Jernelöv and Lann[37] have investigated the effect of covering mercury contaminated sediments with various thicknesses of silicate minerals, clay, and inert minerals. It was found that for systems without macroorganisms, formation and release of methylmercury occurred almost entirely in the upper centimeter (0.4 in.) of the sediment. The presence of Tubificadae (sludge worms) in very high amounts increased the active depth, but the major contribution to the formation of methylmercury was still limited to the upper 2.5 cm (1.0 in.) of the deposit. When dense populations of Anodonta (mussels) were present, the depth to which deposits of inorganic mercury contribute to methylation was increased to about 9 cm (3.5 in.). On the basis of these studies, it appears possible to prevent release of methylmercury from sediments by covering with a 3-cm (1.2 in.) inert layer provided either no macroorganisms or only Tubificidae are present. With Anodonta, a covering layer of about 10 cm (4 in.) would be required.

203. Pratt and O'Connor[38] have reviewed the characteristics of benthic invertebrates found in Long Island Sound in order to estimate the maximum penetration of sand cover that might occur in that location due to biological disturbance. Most

benthic species occurred at depths less than 10 cm (4 in.), but two species penetrated to depths up to 30 cm (12 in.). However, as Pratt and O'Connor point out, it is difficult to predict what species will recolonize sand after the covering operation, so that to be certain that a covering layer will function as an isolating layer, a 30-cm (12-in.) thickness would be desirable.

204. So far, no direct attempts have been made to restore mercury-contaminated bodies of water in Sweden. Field studies have been conducted in limited areas[37] to determine technical feasibility and costs related to restoration. In one case, tests have been made in a lake to determine the best method for covering banks of pulp mill fiber contaminated with phenylmercury. The cost estimated for covering the 1-km^2 (0.38 mi^2) sludge bank with a 3-cm (1.2 in.) layer of sand was $350,000 to $500,000 for spreading from boats and $120,000 for transportation of sand to the site. At another Swedish lake, experiments were conducted on covering of sludge deposits with mine tailings spread from a raft. The particle size of the tailings was 0.02 to 0.20 mm. Sampling showed that as a result of the covering operation, 90 to 95 percent of the test area was successfully covered with 0.2 cm (0.08 in.) or more of mine tailing.

205. Landner[39] has also reported on experiments to restore lakes contaminated with mercury. A 5-cm (2.0-in.)-thick layer of sediment contaminated with phenylmercury was covered by a 0.5- to 1-mm-thick layer of lime and, in another test, by a 5-mm-thick layer of sand. With the lime, methylmercury in test fish was reduced by a factor of 5. A significant reduction was also noted with the sand layer. Although methylmercury was reduced, this effect was not observed when phenylmercury was used.

206. Landner also conducted tests in lakes where freshly ground quartz mineral was spread over the bottom to attempt to seal methylmercury in place. The results obtained were inconclusive because of the difficulties associated with obtaining a uniform layer on the bottom. Due to a shortage of funds, the quartz was barged to the site and then spread by hand, using shovels. This method left large patches of the bottom exposed.

207. Feick, Johanson, and Yeaple[40] conducted aquarium studies with organic and inorganic mercury and evaluated the effectiveness of several covering materials (sand, kaolin clay, silica, zinc sulphide, milled pyrite, ZnS-FeS, thiols, and polyethylene). Tests were also conducted on combinations of these materials, (e.g., a chemical complexing agent below a sand barrier). They found that oxidizing of the polluted sediments resulted in increased availability to the ecosystem, hence the desirability of a blanket or cover to keep the sediment anaerobic. Plastic films (polyethylene) did not appear to be effective barriers for retaining methylmercury. In dredging simulation, they found that about 99 percent of the mercury present remained bound to particulate matter. This implies that, to control the spread of heavy metal pollutants, dispersion and resuspension should be avoided.

208. Bongers and Khattak[41] investigated the effectiveness of sand and gravel as a cover for mercury-contaminated sediments. The release of toxic mercurials by mercury-enriched river sediments was examined in the laboratory. These tests indicated that about 1 μg of methylmercury was released per square meter per day. The release of such toxic mercurials could be prevented by a layer of sand, 6 cm in thickness, applied over the mercury-enriched sediments. Layers of fine or coarse gravel (6 cm deep) were as effective as sand. Thinner layers of

sand, 1.5 and 3 cm in thickness, appeared to be unsatisfactory. The cost of applying 7.6 cm (3 in.) layers of sand or gravel over contaminated river sediments is estimated to be about $3000 to $4000/acre.

209. Echelberger and Tenney[42] treated a eutrophic lake with fly ash to study the effect of that material on phosphorus concentrations. It was concluded that settled fly ash served as an effective barrier to the release of phosphorus from the bottom sediments into the overlying water. Properties of fly ash which contributed to effective removal of phosphorus from the water column and sealing of the sediment were adsorption of soluble organic matter, precipitation of inorganic phosphorus, pozzolanic properties that enhance sealing of the sediment, and a sufficiently high settling rate that allows the fly ash to settle readily. The sealing was considered to be essentially permanent for sealing of small lakes since the minimum velocity to cause scour of the surface has been found to be greater than 20 cm/sec.

210. Covering of mercury-laden sediment with an overlay of crushed steel topped with sand has been investigated in laboratory experiments by Smith.[43] The purpose of the steel, in the form of crushed automobiles, was to remove divalent mercuric ions and methylmercury ions by converting these soluble forms to elemental mercury. The studies showed that such a system rapidly and efficiently removed mercury ions. An overlay of 10 to 15 cm (4 to 6 in) of sand or other finely divided inert material was recommended to prevent erosion and shifting of the steel. Sand would also reduce the rate of diffusion of mercury and thus allow more opportunity for complete chemical reactions with the iron.

211. McKeown et al.[44] have conducted laboratory studies on the oxygen demand of benthal deposits of paper mill wastes and the effect of covering such deposits with a layer of inert sand.

A layer of only 1.0 cm of sand was sufficient to reduce the oxygen-demand to approximately one-half that of the uncovered sludge. Sand layers of 1.5 and 3.0 in. were also used. Considerable compression of the sludge was noted along with a release of oxygen-demanding materials in the water squeezed out. In one case, the sand penetrated the unconsolidated sludge rather than forming a layer on the surface and a second layering was required. Following a short period of increased oxygen demand, the covered deposits settled down to a lowered oxygen demand rate due to the presence of the cover.

212. Materials and methods for control of turbidity caused by disturbance of the sea floor have been investigated by Roe et al.[45] for the U.S. Navy. After considering the use of flocculating agents, stabilization of the soil mass with binding materials injected into the sediment, and formation of an overlay to cover the sediment, it was concluded that an overlay was the best solution to the problem. Possible methods for creating an overlay that were studied included polymer gel, formation of a gel by increasing the viscosity of a liquid, and formation of a plastic film at the site by casting from a solvent system. The plastic film approach was chosen as the best system to solve the turbidity control problem. A plastic formulation was developed and a dispersing system designed.

213. Under contract to EPA, Widman and Epstein[46] continued the Navy work on polymer film overlays but with emphasis on preventing leaching of mercury from sediments. Concepts for dispensing polymer films under water and over mercury-contaminated sludges were generated. The candidate systems examined were based on coagulable materials, hot-melt polymer compounds, and preformed films. A large number of laboratory blends of the candidate materials in the first two categories were made and qualitatively evaluated to identify

promising formulations. Experimental equipment appropriate to each concept (including preformed films) was designed, and experiments were conducted in an 18-ft-long test tank to establish the feasibility of the material-equipment systems. The results of these experiments suggested that commercially available, preformed films could be successfully dispensed from a roll and applied as an overlay on the mercury-contaminated sludge. A cost analysis showed that a preformed film overlay can probably be deployed for 1.5¢ to 3.3 ¢/sq ft, hot melt films for about 2.5 ¢/sq ft, and a coagulable nylon film for about 4 ¢/sq ft.

214. An EPA report on measures for restoration of lakes[47] has pointed out a number of problems that might be encountered in covering operations. First, production of gas within the sediment may cause ballooning of plastic sheeting or rupturing of a layer of particulate material. Second, small-size particles were considered to be best suited for sediment covering since larger particles might tend to sink below flocculent sediments that are insufficiently consolidated. Third, covering of sediments with fly ash may create new problems since fly ash frequently contains impurities, including heavy metals.

Methods of Applying Cover

215. The object of any covering method is to deposit in a practical manner a uniformly thick layer of cover material over the dredged material that fills the entire borrow pit. If possible, the method should be a single operation designed so that the cover material is distributed evenly and arrives on the bottom at sufficiently low speed that the particles do not displace the dredged material or sink into it. At the same time the settling velocity cannot be so low that the cover is carried away by current and settles outside the pit area.

216. The cover cannot be laid down by making discrete dumps that form an array of mounds on the bottom. The impact

energy would be great enough to displace and resuspend the dredged material causing it to be either carried out of the pit by ambient currents or to eventually settle out on top of the cover material. Natural erosion of the cover material, even if it has a lower erosion threshold than the dredged material, is not a dependable way of spreading the mounds into a uniformly thick layer. However, if the erosion threshold of the cover is greater than that of the dredged material, the latter will be eroded away before the cover can be spread by natural processes.

217. In the following sections, methods are examined for laying a uniform cover with low impact energy; each method requires the use of a seagoing hopper dredge. The first method distributes the cover material by means of two spray booms that lay down a wide swath on each side of the vessel. The spray booms are supplied by the pump-out system, and the cover material is stored in the hoppers. The spray boom method is limited to noncohesive materials whose settling velocities are approximately 0.5 ft/sec. A second method is briefly presented that uses the same pump-down technique for covering that was recommended to extend the dumping capability of the hopper dredge at borrow pits. The covering material is pumped out of the hoppers and discharged through the submerged dragarm in the proximity of the bottom with zero impact energy. This second method, however, places untenable requirements on the vessel with regard to navigation. A third method, broadcasting systems, is also considered.

Spray boom system

218. The spray boom system deploys the cover material by spraying it on the surface of the water and letting it sink rapidly to the bottom where it builds up a cover layer on top of the dredged material in the borrow pit. The covering operation is carried out using a seagoing hopper dredge with direct pump out that is equipped with two spray booms (port and starboard) and

the craning facilities required to handle them. The cover material is stored in the hoppers and, using the main dredge pumps, is pumped out through the collection system to the spray booms. It is slurried by jetting water in the hoppers and by mixing water at the pump inlet and is sprayed out at a solids ratio of 15 to 20 percent. Each boom lays down an even spray over a width of 85 ft so that with both booms operating, two 85-ft-wide swaths are laid down with a separation distance of approximately 85 ft. The configuration is shown in Figure 18 below.

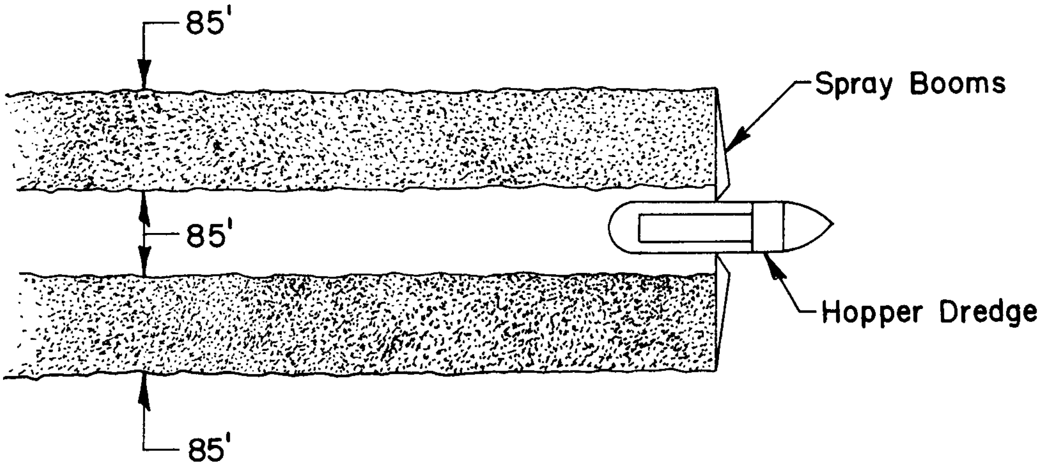


Figure 18. Spray cover configuration

219. The spray method for applying the cover requires that the material settles to the bottom before it can be transported away from the dump point. If the average water depth were 50 ft, the settling time would be 10 min for fine sand and

approximately 1 min for coarse sand or fine gravel. The hopper dredge is particularly well suited for sand and gravel operations because by dredging beyond overflow, it can consolidate and compact the load and thereby maximize the capacity of the vessel.

220. The hardware system required to implement the spray method is the same as that described by Tobias for the dredge GOETHALS in connection with a feasibility study of its use as a sand-spreading vessel.[48] Figure 19 shows the design and arrangement of the booms as proposed in the study. Using the cost figures compiled by Tobias as a reference, it is estimated that the spray boom modifications for the dredge GOETHALS would cost $200,000 at 1975 prices.

221. A typical example of a spray-covering operation illustrates the practical considerations that control the situation. The dredge GOETHALS is to cover a borrow pit that is 1 nautical mile long by 1/2 nautical mile wide with a 12-in.-thick cover of coarse sand. The GOETHALS can store an average of 4000 cu yd of wet sand in its hoppers and its dredge pumps can deliver 600 cu yd of mix/min. The sand source is 10 miles away and the sand must be dredged. The GOETHALS can operate around the clock six days a week, the seventh day being a lay day. For these assumptions the number of dredging and covering trip cycles will be:

Total volume of sand transported	=	684,000 cu yd
Capacity of GOETHALS	=	4000 cu yd
No. of cycles	=	171

222. The GOETHALS lays down the cover at 2 knots, while running at full pump capacity with an effective spray width of 170 ft. The sand mixture is controlled at 20 percent solids by volume.

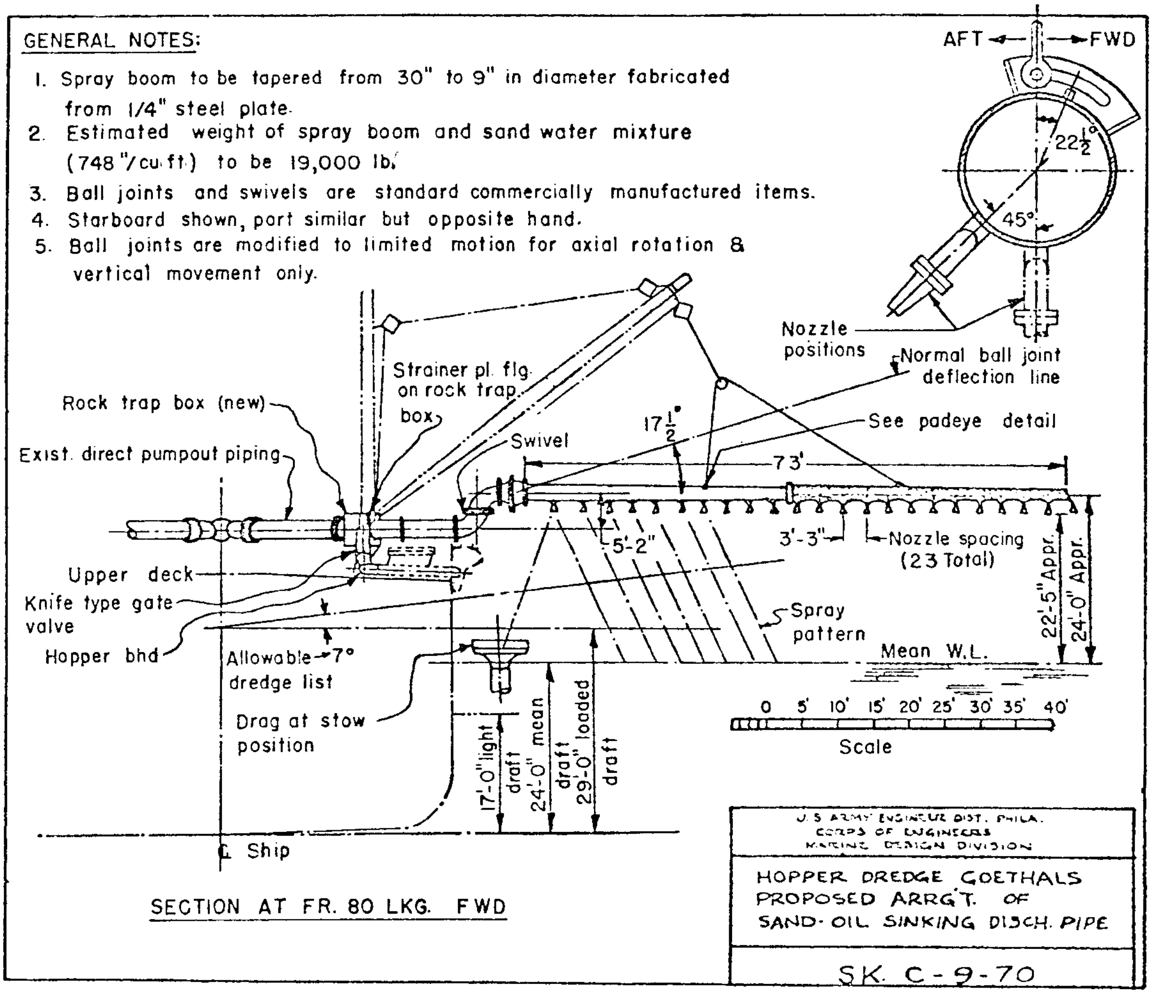


Figure 19. Proposed spray bar arrangement

Total volume of mixture pumped	=	20,000 cu yd/cycle
Total pumping time	=	33.3 min/cycle
Thickness of cover	=	0.63 in/pass
Total distance travelled	=	1.1 nautical mile/cycle

223. The pattern of covering is alternated by laying down a single-pass cover along the 1-nautical-mile length of the pit, followed by the next cover thickness along the 1/2-nautical-mile width. This procedure eliminates holes or troughs in the cover. According to the total distance traveled while dumping, the dredge dumps its load in a single pass along the 1-nautical-mile direction and in two passes when running parallel to the 1/2-nautical-mile width direction.

224. The cycle time for the dredge breaks down as follows:

Loading sand	2 hr
Trip to borrow pit	1 hr
Cover	1 hr
Return trip	1 hr
Cycle time	5 hr

225. Navigation while laying down the cover can be provided with several buoys in the dump site plus a precision system such as Raydist. Loran C would be marginal, even in the repeatability mode: that is, using the readings to return to the same spot and then move over the required distance each time. Thus, the cost of setting up a precision navigation system must be added to the cost of covering, unless that system were already established to be used during filling. It should be pointed out that the navigation requirements for covering are more stringent than for filling the pit and may require a more sophisticated system than Raydist to minimize the redundant runs necessary to obtain a satisfactory cover.

226. Costs for covering can be estimated as follows, for the case described above. Based on a 5-hr cycle time and 171 cycles, the total operating time is 855 hr or 6 calendar weeks to lay a 12-in. cover on a 1/2-square-nautical-mile (424 acres) borrow pit. The operational cost of the dredge based on a daily rate of $15,000 for 42 operational days and 6 days for mobilization and demobilization of the spray boom system comes to 48 days or $720,000. This amounts to $1.05/cu yd of cover, for a 12-in.-thick cover, or $1700/acre. Since there undoubtedly will be holes in the cover, without regard to the navigation system used, approximately 50 percent should be added to this number to allow for redundant runs, bringing the cost for dredge operation alone to about $2500/acre. The cost of modifying a dredge has been estimated to be $200,000. Finally, the cost for renting a precision navigation system must also be added.

227. It should be stressed that this cost is for covering a relatively large pit. Smaller pits would be somewhat more expensive to cover since the time spent maneuvering and getting into position for multiple short runs would increase the total dredge time required per acre of cover.

Pump-down method

228. The pump-down method employs a seagoing hopper dredge that is equipped with a direct pump-out system and is modified to discharge the hopper material through the dragarms. This is the same system as was previously recommended for dumping a hopper dredge at the borrow pit except that cover material is discharged rather than dredged material. The operation is characterized by the following features:

- a. Dragarms are lowered so that dragheads discharge within a few feet of the bottom.
- b. Ship's speed is set equal to the discharge velocity to discharge horizontally.

c. The cover material discharges at zero impact energy with respect to the bottom.

229. Using the same rule here that applied to the spray method, the cover material must settle the few feet within a short time in order for its placement accuracy to be reasonable. The settling velocity of the material can be less than for the case of surface discharge so that finer sand may be used.

230. The hardware cost required to implement the pump-down method for laying a cover is the same $150,000 estimated earlier to add the capability of pumping down the hopper dredge dragarms.

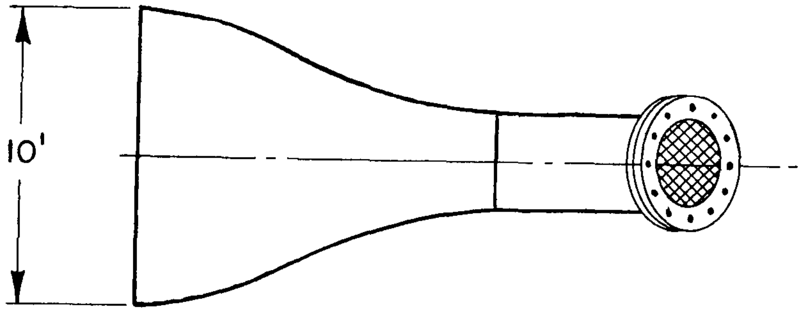
231. The example of the spray boom method can be used for the pump-down system with the exception that the GOETHALS will lay the cover at 5 knots since this provides more favorable dispersion at the draghead. At full pumping capacity the velocity in the dragarm is 24 ft/sec, and the draghead is shaped so that the discharge velocity is 5 knots (8.44 ft/sec) and in the horizontal plane. Since the diameter of the dragarm pipe is 32 in. ID, its flow area is 5.59 sq ft and the discharge area of the draghead is therefore 16 sq ft. The width of the discharge slot is 10 ft and the height of the slot is 19 in. The draghead configuration is shown in Figure 20 and incorporates the means of adjusting the turning angle to the horizontal. The total volume of mixture pumped is unchanged at 20,000 cu yd/cycle as is the pumping time of 33.3 min/cycle so that:

Thickness of cover = 3.84 in./pass

Total distance traveled = 2.78 nautical mile/cycle

The 12-in.-thick cover is accomplished in 3 layers, each approximately 4 in. thick.

232. Unfortunately, this method tremendously complicates the navigation problem and is only marginally feasible in locations



$$\text{AREA RATIO} = \frac{(Ax)\ \text{DISCH.}}{(Ax)\ \text{INLET}} = 2.86$$

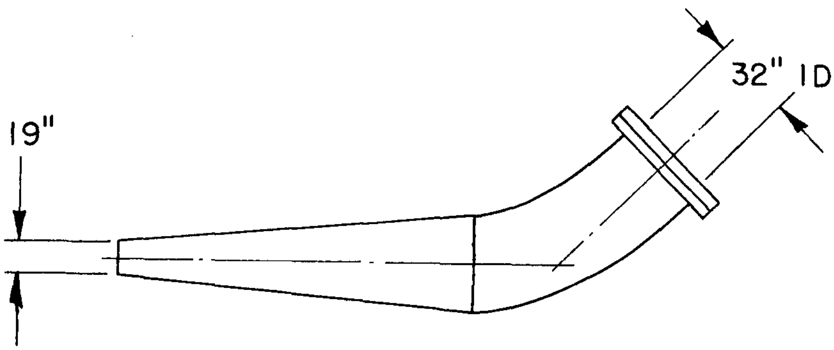


Figure 20. Discharge head for pump-down covering operation

near enough to shore, or to fixed towers, to allow the installation of a highly precise navigation system such as used for pre-dredging surveys. These systems have relatively short ranges, approximately line of sight. The basic problem is that the draghead will only lay down a 10-ft-wide strip, thus requiring highly precise navigation to ensure a uniform cover.

Broadcasting systems

233. A third category considered was broadcasting systems, such as used to broadcast seed. In theory, these could generate a cover of approximately the same width, and thickness, as the spray boom system and for approximately the same cost. However, since they would require substantial changes in the plumbing on the dredges, this approach does not appear to offer any advantage over the spray boom system.

Feasibility of Covering Borrow Pits

234. The concept of sealing a polluted area with a cover of clean material has been discussed for several years. However, the technical, operational, and economical constraints have always been discouraging. After considerable analysis and experimentation, the Swedish Government abandoned this approach as too costly. Based upon the literature review, discussions with operating personnel, and the analysis in the previous section, the following conclusions were reached:

a. Although covering systems using plastic sheets and fly ash have been investigated, the most suitable material for covering dredged materials is sand. This is particularly true in the case of borrow pits because borrow pits will always exist in areas of extensive sand deposits where cover materials will be readily available.

b. The thickness of sand required to prevent burrowing of benthic organisms into the polluted layer depends on the organisms encountered at the particular location. A minimum of 10 cm (4 in.) would be necessary with a 30-cm (12 in.) thickness more desirable.

c. When the sediment to be covered consists of a loose flocculent material, the intended cover may penetrate the bed and be ineffective. It is important to consider the bed surface characteristics and how they may change with time. At present, information is not available to form a basis for estimating how soon a bed may be covered after depositing.

235. An additional factor on covering of dredged materials needs consideration: how fast will the borrow pit be filled, and how does this time delay relate to the effectiveness of covering? The purposes of covering are to reduce the availability of pollutants to the environment and/or to reduce the tendency for erosion. Covering methods require that fairly large areas be covered at one time. Since filling the borrow pit requires many loads, it does not appear feasible to conduct the covering operation any more often than every few weeks or months. However, during the period while the pit is partially filled, both leaching of pollutants and erosion of the unconsolidated sediments will be most severe. As time goes on, formation of an oxidized surface layer, consolidation, presence of certain benthic organisms, and possibly even natural covering due to transport of nearby sand onto the dredged material will act to decrease the adverse impact of the polluted dredged material. Thus, when the cover is most needed, it will not be in place, and later, when the need is somewhat less, the cover can be established. Decisions concerning the value of covering will depend on consideration of the environmental impact and economics in each case, but an initial delay in covering is unavoidable.

236. In general, it does not appear to be realistic to place the cover over the pit before considerable consolidation has taken place and, once it has, there probably is no need for the cover. Field data will be required to verify this conclusion.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

237. Borrow pit dumping is feasible using hopper dredges, provided that an auxiliary navigation capability is supplied either with an instrumented buoy in the center of the dump or a precision navigation service such as Raydist. Both methods are readily available and may be quickly implemented.

238. Borrow pit dumping using tugboats and barges is only feasible under ideal conditions due to the lesser navigation suite on tugs, as compared to hopper dredges, and due to the poor control that the tug may exert on the position of the barge. A further complication is the almost total lack of communications between the barge and the tug.

239. Feasibility requires that the borrow pits be several acres in size and have dimensions sufficient to allow a radial spreading of approximately several hundred feet. Field studies of dump sites indicate that most of the material ($\sim$90 percent) is contained within 400 ft radially from a vertical line through the dump point.

240. Bottom-dumped dredged material partitions into a main cloud that descends vertically and a turbidity cloud that is spun off during the dumping and descending phases. The main cloud appears to descend at a high velocity, impact at the ocean bottom, and then collapse onto the bottom. The main cloud should experience negligible effects due to ambient water current and variations in water density. The turbidity cloud will most probably be moved out of the general dump site area by even the smallest currents. Compared to the main cloud which descends to the bottom, the turbidity cloud is very small in terms of total solids.

241. The short-term behavior of the main cloud predicted by mathematical models is in general agreement with field data and field observations. However, the predicted vertical descent velocity is substantially higher than the one set of field data measurements available. Predicted collapse radius on the bottom and field observations are in general agreement, but questions remain as to whether the models correctly represent the physics of the situation.

242. Field data on the actual results of a discrete dump are inadequate to assist in estimating the short-term fate of dredged material. Most measurements and observations have been made well after the dump rather than before, during, and after. Little is known quantitatively of the partitioning of the material into the main descending cloud and the turbidity cloud that remains in the water column. The dynamics of the impact and collapse of the main cloud are important in establishing the fate of the material, but almost nothing is known about these, other than what is predicted by the Koh-Chang model. A density layer flow is hypothesized but has not been observed except in the operation of pipeline dredges.

243. Substantial mathematical modeling has been accomplished and is best represented by the Koh-Chang and Krishnappan models. The former, although simple to use, is extremely complex and comprehensive; the latter is simple and only addresses a portion of the problem (bottom dumping). A sensitivity analysis indicates that for the case of large dumps in shallow water much simplification can be made to the Koh-Chang model without sacrificing output resolution. Several errors exist within the computer programming which must be resolved before the Koh-Chang model can be considered fully programmed. The model cannot adequately handle a realistic current field. A three-dimensional, time-variable current field could be

programmed, but the required input data would most probably not be available so that this phase of the model would find little use in the field. The Krishnappan model is simple and predicts cloud size, descent velocity, and the height of the deposit on the bottom. Although none of these predictions have been field verified, they are based upon laboratory tests. The model is not comprehensive enough, in its present form, to handle some cases of interest and it inadequately describes the early stages of descent, in terms of velocity.

244. At the present time, estimates cannot be made of the long-term fate of material placed in a borrow pit. If the material is cohesive, and that is the case of interest, consolidation takes place and the water velocity necessary to cause erosion and resuspension is dependent upon how long the material has been in the borrow pit. Indications are that it may take weeks, or months, for the material to consolidate to the point where its erosional resistance is comparable to that of fine sand. Until better information is available, borrow pit areas should be selected so that their bottom current is 0.1 ft/sec or less and the dumping should be done at a time of year to allow several months for consolidation to take place prior to the storm season, when ocean storms in the area may generate substantial bottom currents.

245. Little is known about the geometry and hydraulic conditions that will exist in future borrow pits. Indications are that the pits will tend to be large due to the complexity involved in obtaining a permit and the cost of setting up the dredging and processing operation. If large, the effect on local currents will be minimal and the pit will most probably not become stagnant. Pit walls, with slopes typically 1:8 to 1:20, do not appear to be an obstacle to a density layer flow, but this flow, if it occurs with bottom dumping, appears to extend only for a few hundred feet. If stagnant conditions do exist in a borrow pit, the presence

of hydrogen sulfide will assist in complexing any heavy metals in the dumped material. This suggests the possibility of dumping the most highly polluted material into the pit first, and topping off the pit with less polluted material. Finally, it may be possible to reduce the transport of fine material out of the pit by using silt curtains around the pit and across the pit to affect the local currents. Available curtains could be made to stand off the bottom by simply increasing the weight of the chain ballast and thus provide a 30-ft barrier around the pit.

246. It is technically feasible to modify a hopper dredge so that it can be used to place a cover of clean sand over a borrow pit. The modifications will cost approximately $200,000 and the cost to cover a large pit will be about $2500/acre plus the cost of rental service for a precision navigation system. However, the pit cannot be covered for a period of time determined by how long it takes the material in the pit to consolidate to the point where it can support the weight of the cover. By the time that this consolidation takes place, any surface pollutants may have leached out and the dredged material erosional resistance will probably be approaching that of the sand cover. Since the cover cannot be placed when it is most needed to retard the leaching of pollutants, and since after a period of time the erosional characteristics of the original material appear to be better than the sand cover, there is little reason to put the cover over the pit. If pits are selected in locations where the bottom current is small, covering does not appear to be warranted.

Recommendations

247. As a matter of the highest priority, a series of carefully designed laboratory and field measurements should be conducted to identify and quantify the physical mechanisms that are important in open-water disposal. The field measurements

program should be designed and conducted in a manner such that it yields sufficient data to examine the premises of existing models and to serve as the basis for possible simplification of these models and development of any future models that may replace or augment them. Additional research should be conducted on the mechanisms at work when dredged material is dumped in open water, rather than on the gross transport of the material. There has been extensive effort in the area of sediment chemistry, but the area of sediment physics has been ignored. The effect of different dredging techniques and the importance of water content, compaction, and cohesive strength has not received sufficient emphasis, nor have flocculation and hinderd settling. There is a need to identify the physical mechanisms at work and to establish their relative importance, so that the model complexity is included where warranted and excluded where not warranted.

248. It is recommended that the user requirements for predicting the short- and long-term fate of dredged material dumped in open water be established. A clear understanding of user requirements will be valuable in guiding future mathematical modeling of open-water dumping.

249. The horizontal pump-down concept developed in this investigation should be demonstrated in the field. Pumping the material down a dragarm and canceling out its horizontal discharge velocity offers the possibility of laying dredged material on the bottom with virtually no dispersion. It could also reduce the surface turbidity plume from hopper dredge overflow to the point where overflowing might again be feasible resulting in increased efficiency in the dredging operation. This horizontal pump-down evaluation should be conducted in concert with other field measurement programs so that the relative dispersion and turbidity generation from conventional bottom dumping can be compared to that using

horizontal pump down for the same materials. A single dredge could conduct both bottom dumping and horizontal pumping by dumping two hoppers and then pumping down the other two.

250. Studies should be conducted on several materials to establish the time dependency of the buildup of cohesive strength after deposition of dredged material and to determine the water current velocity necessary to cause erosion and resuspension. These studies should be conducted in situ at typical dump sites using representative materials. The horizontal water current structure should be examined in situ for both borrow pits and locations adjacent to the pits so that the effects of this current on dumped material can be assessed once the time-variable consolidation characteristics have been determined. Finally, the energy available for resuspension and erosion due to storms in typical borrow pit areas should be measured. The net transport due to the storms and other currents should also be established.

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APPENDIX A: PARAMETRIC EVALUATION OF THE KOH-CHANG MODEL

1. For the purpose of this study, the Koh-Chang model for ocean disposal from a barge was considered to be the best available descriptive model to assist in decision making concerning dispersion of dredged material. This Appendix presents the results of the study made to assess the application of the Koh-Chang model to predict the behavior of dredged material after open-water disposal.

2. The Koh-Chang model is a recent development having been published only a few months before this study began. Thus, there has been very little practical experience gained by other researchers concerning its use. In the report presenting the model,[29*] several sample computer runs are given that provide not only typical input values for various types of waste materials, but also computer plots of output dependent variables.

3. The model is complex both mathematically and in the computer techniques required to produce a solution. Fundamental assumptions are made in the description of the physical processes governing dispersion (convenctive descent followed by dynamic collapse and then long term dispersion). Direct field observations of these phenomena have not been made, and until field studies are conducted to verify the model, there will remain doubt concerning its validity.

4. The EPA National Environmental Research Center provided the authors with several example computer runs along with decks of program cards, which greatly assisted in operation of the model. However, given the complexity of the model, its lack of field verification, and the newness of the model with the resulting lack of experience by others in its operation, it was considered valuable to produce a number of trial runs of the program to gain familiarity with its operation.

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*References are given in the References section following the main text.

In addition to gaining experience running the program, the parametric evaluation process was designed to indicate which input parameters produce the greatest effect on the output. These sensitive parameters could then be considered in more detail.

5. A large number of data inputs are required by the program. Prior to running the computer, these input variables were divided into three categories depending on the degree of control that might be exercised over the dumping operation in the field:

- a. Operational parameters where opportunities may exist to optimize placement of dredged material (i.e., water depth, dump size, initial velocity of dump, and dredged material characteristics).

- b. Oceanographic parameters that may allow optimized dumping by selecting the best conditions for dumping (i.e., ambient water density profile, ambient water velocity, horizontal diffusion factor, and vertical diffusion coefficient).

- c. Hydrodynamic parameters where little or no control is possible (i.e., drag coefficient, gradient factor in the cloud, absorbency coefficients, entrainment coefficients, and particle settling coefficient).

6. The model was then examined to determine how each of these physical factors is included in the model: that is, which mathematical expressions are used to describe the dispersion process. This information is readily available from the discussion of the model provided by Koh and Chang.[29] For each of the parameters a constant value is input. In all cases some range of values is possible either to account for varying field conditions (e.g., water depth) or because of uncertainty in the proper value for a parameter which should be relatively constant (i.e., drag coefficients).

7. A literature search was conducted to determine both the likely range of values for each parameter and what could be termed "typical"

or standard values. Standard values selected are shown in Table A-1. The parametric evaluation was conducted by varying each parameter in turn over the range of possible values. For each of these runs all other parameters were held constant at the standard values. Although this procedure provided a simple and orderly approach to the model, possible effects due to interactions among the parameters were ignored. However, at this stage of model development, these additional refinements do not appear warranted. As more experience is developed working with the model and field verification becomes available, then more detailed examination of the model will be available. It appears that in some aspects the model is unnecessarily complex for this mode of dumping and that in other areas a more sophisticated approach may be required.

8. Not all parameters were varied. In some cases it appeared that a parameter had very little effect on dredged material dumping in the specific case of relatively shallow water. Other parameters were eliminated from this evaluation because the literature does not contain sufficient information for rational choices to be made. In both of these cases, most values used were those of Koh and Chang.

9. The output of the Koh-Chang model consists, at each time interval, of a description of the location of the cloud, the cloud geometry, the amount of solids in the water column, and, during the diffusion stage, a description of the geometry of solids deposited on the bottom. For each run the model output consists of many pages of data. To provide a simplified presentation of model output, it was decided to depict the dumping operation by the following parameters:

a. The maximum cloud velocity during convective descent.

b. The impact velocity of the cloud on the bottom.

c. The percent of the total solids deposited after 25 min.

Table A-1

Standard Input Parameters Selected for Operations of the Koh-Chang Model

Operational Parameters	Input
Water Depth	50 ft
Dump Size	20-ft radius
Initial Release Velocity	0.0 ft/sec
Dredged Material Characteristics	
Particle Settling Velocity	0.005 ft/sec
Solids Concentration	50 percent
Solids Specific Gravity	2.5
Oceanographic Parameters	
Ambient Density Profile	1.023, 0 to 30 ft linear 1.023 to 1.030 between 30 and 40 ft 1.030, 40 ft to bottom
Horizontal Diffusion Factor	0.001
Vertical Diffusion Coefficient	0.05 ft^2/sec*
Ambient Water Velocity	See Discussion
Hydrodynamic Parameters	
Cloud Drag Coefficient	0.50
Form Drag Coefficient	0.50*
Ellipsoidal Wedge Drag Coefficient	0.10*
Plate Drag Coefficient	1.00
Entrainment Coefficient for Thermal	0.25
Entrainment Coefficient for Collapse	0.001*
Added Mass Coefficient	1.5
Friction Coefficient, Cloud to Ocean Bottom	0.50*
Skin Friction for Collapse	0.01*
Friction Modification Factor	0.10*
Particle Settling Coefficient	0.00*
Gradient Factor in the Cloud	0.25*
Absorbancy at the Bottom	1.00*
Entrainment at the Bottom	0.00*

*In evaluating the model, these values were held constant.

Table A-2

Variation of Water Depth

Water Depth ft	Convective Descent Velocity, ft/sec		Cloud Radius at Impact ft	Percent Deposited in 25 min	Bottom Deposit, ft	
	Max.	Impact			σ	h
25	12.4	12.4	24.0	74.8	108	0.175
*50	13.1	12.7	29.8	77.4	136.5	0.14
100	13.1	9.8	41.2	82.4	186	0.065
150	13.1	7.6	52.7	86.6	235	0.048

*Standard Value

Table A-3

Variation of Dump Size

Dump Size Radius ft	Dump Volume yd^3	Convective Descent Velocity, ft/sec		Percent Deposited in 25 min	Bottom Deposit, ft		Multiples of Maximum Dump	Cum. Deposit Height ft
		Max.	Impact		σ	h		
5	4.9	6.5	3.0	82.4	48	0.018	506	9.1
10	39	9.2	6.9	78.8	76	0.057	64	3.6
*20	310	13.1	12.7	77.4	136.5	0.14	8	1.12
30	1046	15.9	15.9	77.8	201	0.22	2.37	0.52
40	2479	17.5	17.5	78.3	267	0.29	1.0	0.29

*Standard Value

d. The distribution of the deposited solids in the bottom.

e. The height of deposited solids.

f. In some cases other output parameters were noted when considered valuable.

10. To calculate the height of solids from the total solids dumped and the variances of the deposit, it is necessary to assume a distribution for the material. The simplest assumption would be a normal or Gaussian distribution; since there is no evidence at this time that such an assumption is not the actual case, a normal distribution was used.

Operational Parameters

Water depth

11. As discussed earlier, water depth over existing borrow pits ranges from about 20 ft to a maximum of about 100 ft. While improved technology may allow dredging to almost any depth, future borrow pits will most probably occur in less than 150 ft of water. The typical value was considered to be 50 ft. Program output resulting from water depth being varied is shown in Table A-2.

12. The velocity of the dredged material cloud is seen to accelerate to a maximum of 13.1 ft/sec at a depth between 25 and 50 ft, after which the velocity decreases due to entrainment of ambient water into the cloud thereby increasing the cloud volume and the drag forces. From an initial radius of 20 ft, the cloud has grown to 52.7 ft in 150 ft of water.

13. The percent deposited at 25 min is seen to increase as the depth increases. While this may appear to be a trend opposite to that which might have been anticipated, the reason for this behavior is that the

low impact velocity of the cloud at greater depth produces lower horizontal spreading velocity and subsequently more rapid settling from the turbulent cloud. Although the spreading is slower, the distance of spread is greater due to the far greater cloud volume caused by the additional entrainment occurring as the cloud descends to greater depths.

Dump size

14. Variations in program output with varying size of dump are shown in Table A-3. The smallest dump size corresponds to a dump from a single hopper of a compartmented barge, and the largest size represents a large split-hull dumping barge or a compartment of a hopper dredge. Small dumps produce considerably lower impact velocities and bottom deposits. An interesting observation is that if dumps could be controlled so that many small dumps were made at exactly the same location, then the cumulative deposit would be many times as high as a single large dump of the same volume. While many arguments can be advanced to suggest that the results indicated in Table A-3 would not be reproduced in the ocean (positioning problems, resuspension due to subsequent dumps, angle of repose of deposited material), the trend of the data clearly indicates that repeated dumps of smaller amounts of material would do much to minimize spread resulting from the dumping operation itself. There probably is an optimum size dump for a given set of conditions, but its determination must await field verification of the model.

Initial release velocity

15. It was considered that the initial dredged material release velocity at the water surface may have an effect on the dispersion process. Computer output for variation in initial velocity is shown in Table A-4. It is evident that the initial velocity is a very insignificant factor in the model due to the high fall velocity rapidly achieved during the convective descent process. Although some control of the initial

Table A-4

Variation in Initial Velocity

Initial Velocity ft/sec	Convective Descent Velocity, ft/sec		Percent Deposited in 25 min	Bottom Deposit ft	
	Max.	Inpact		σ	h
*0	13.1	12.7	77.4	136.5	0.14
1	13.1	12.7	77.5	136.5	0.14
3	13.1	12.8	77.6	136.5	0.14
5	13.3	12.8	77.6	136.5	0.14

*Standard Value

Table A-5

Variation in Dredged Material Characteristics

Solids Concentration Volume %	Solids Density g/cc	Particle Fall Velocity ft/sec	Convective Descent Velocity, ft/sec		Percent Deposited in 25 min	Bottom Deposit, ft		Volume Dumped ft^3
			Max.	Impact		σ (ft)	h (ft)	
10	2.5	0.005	6.2	5.7	84.4	113	0.04	1674
30	2.5	0.005	10.4	9.9	79.5	127.5	0.10	5020
*50	2.5	0.005	13.1	12.7	77.4	136.5	0.14	8364
50	1.75	0.005	9.5	9.0	79.5	123.5	0.17	8366
50	1.25	0.005	5.4	5.0	82.7	107.5	0.23	8369
50	2.5	0.0005	13.1	12.7	10.9	139.1	0.14	8378
50	2.5	0.05	13.1	12.7	100	105.5	0.24	8357

*Standard Value

velocity might be possible during the dumping operation, the model predicts that the effect on precision placement would be negligible.

Dredged material characteristics

16. One of the obvious uncertainties concerning inputs to the Koh-Chang model is the representation of the suspended solids. For each type of material three descriptions are required: solids concentration, solids density, and fall velocity of the particles. A total of eight different solids are allowed: four different densities with up to two fall velocities each. In addition, the combination of all solids types is used to calculate the overall density of the dredged material dump being simulated. To investigate the variation in model prediction with changes in material characterization, a total of seven runs was made as shown in Table A-5. Although a wide range of concentrations and densities was run, very little difference is noted in the output except for changes in particle fall velocity. Low solids concentrations result in low cloud excess density, slower settling velocities, and somewhat less spread. However, in comparing the dump of 10 percent solids with that of 50 percent solids, the lower solids content results in only about 17 percent less spread. The volume of solids dumped at 10 percent solids is only one-fifth that of the 50-percent-solids dump, and if five consecutive dumps of the lower solids percent were made at the same location, the height of the resulting mound is predicted to be 0.20 ft (discounting erosion of prior dumps by later dumps). This value is only slightly greater than the 0.14-ft-high mound predicted for the 50-percent-solids dump. Thus, Koh-Chang model predictions do not show major differences when the solids content is varied over the range of 10 to 50 percent solids.

17. Similarly, a range of solids densities at constant volume ratio was run as shown in Table A-5. As the density was decreased from 2.5 to 1.25 g/cc, the convective descent velocity was seen to decrease with a resulting decrease in spread of the bottom deposit. However, this decrease in spread of the deposit is only 21 percent.

Thus, particle density variations also do not appear to have a major effect on the spread of the bottom deposit.

18. The third dredged material characteristic is the particle settling velocity. The model has been constructed such that a particle can leave the cloud only when the absolute value of the cloud vertical velocity at the centroid is less than the particle settling velocity. Thus, during convective descent of clouds such as those dumped from hopper dredges or scows, no particles can leave the cloud. During collapse and long term diffusion, the cloud's vertical velocity is low and solids will leave the cloud. To be considered as deposited on the bottom, the particles must still traverse the last few feet at approximately the individual particle settling velocity.

19. There are two phenomena that occur in settling of particles in fairly concentrated slurries that alter individual particle-settling velocities. The first produces a reduction in settling velocity. When numerous particles are dispersed in a fluid, the fall velocity will be less than that for a single particle due to mutual interference of the particles, a process termed "hindered settling." Theoretical and experimental data indicate that for solids concentrations as low as 0.1 percent dry weight, a measurable effect is observed and the reduction in settling rate may be as much as 50 percent at a solids concentration of 8 percent.

20. The second effect is flocculation which increases effective settling velocities. In suspensions of silt and clay, electrochemical forces tend to hold particles together once they come into contact. The size of the floc formed is limited since larger floc have less structural strength and may be sheared apart if the turbulence is too great. If a suspension of fine material is settling in a quiescent fluid, flocculation will occur by particles with greater fall velocities overtaking and adhering to slower ones. Once two or more particles combine they will settle as a group with a greater fall velocity than any of

the individual particles of the group falling alone. Therefore, in a flocculent suspension, the mean fall velocity of the material will increase with time. Even if the time-related dependence of fall velocity were known, the Koh-Chang model can only incorporate constant values.

21. Trial computer runs using different particle fall velocities are shown in lines 3, 6, and 7 of Table A-5. Very significant differences are seen. At a clay fall velocity of 0.0005 ft/sec (33 min to fall 1 ft), only about 11 percent of the solids will have settled out within 25 min. As the fall velocity is increased to 0.005 ft/sec representing a silty sand (3.3 min to fall 1 ft), the percent deposited at 25 min has increased to 77 percent. At a sand settling velocity of 0.05 ft/sec (0.33 min/ft), essentially all solids will have settled out within 25 min. For these trial computer runs, no ambient water velocity was included. The longer solids remain in suspension the greater would be the horizontal transport if a current were present. It is apparent from these computer runs that modifications to the dredged material that would result in increased particle settling velocities would have a very significant effect on dispersion when near-bottom currents are present in the dump site.

Oceanographic Parameters

Ambient density profile

22. Among the oceanographic parameters, it was considered that the ambient density profile might have a strong influence on the ultimate deposition of the dumped solids. The presence of a strong pycnocline might arrest the descent of the cloud at some intermediate water depth and allow it to be transported by ambient currents and undergo diffusion without ever reaching the bottom.

23. Two ambient water densities were investigated. The first was that of no variation of density with depth; the density was maintained at 1.023 g/cc throughout the water column. The second case was that

Table A-6

Variation in Ambient Density Profile

Ambient Density Profile	Convective Descent Velocity, ft/sec Max.	Impact	Percent Deposited in 25 min	Bottom Deposit ft σ	h
ρ = 1.023 g/cc for entire water depth	13.1	12.8	77.3	137	0.14
*0-30 ft, ρ = 1.023 g/cc 30-40 ft, ρ varies linearly from 1.023 to 1.030 g/cc 40 ft to bottom, ρ = 1.030 g/cc	13.1	12.7	77.4	136.5	0.14

*Standard Conditions

Table A-7

Variation in Diffusion Dissipation Parameters

Dissipation Parameter $ft^{2/3}/sec$	Percent Deposited in 25 min	Bottom Deposit ft σ	h
0.01	75.6	149	0.12
*0.001	77.4	136.5	0.14
0.0001	77.6	136	0.14

*Standard Value

of a strong pycnocline with a density of 1.023 g/cc near the surface, 1.030 g/cc near the bottom, and a 10-ft layer between a 30- and 40-ft depth where the density changed linearly between the two values. The computer output for these conditions is shown in Table A-6. It is evident that for these dumping conditions, the presence of a pycnocline has only a very minor effect on the dispersion process and there is no evidence of the cloud tending to collapse at the steep density gradient.

Horizontal diffusion factor

24. The Koh-Chang model considers horizontal turbulent diffusion to be described by a 4/3 power law of the form

$$K_x \text{ (or } K_z) = A_L L^{4/3} \tag{1}$$

Turbulent diffusion in both horizontal directions is assumed to be the same. The term A_L is a constant called the dissipation parameter (with units of $ft^{2/3}$ sec) and is constant for a given environmental system. The term L is a characteristic length of the diffusing patch. Thus, the value of the diffusion coefficient will increase as the diffusing cloud increases in size. This relationship has been shown to be at least approximately correct for turbulent diffusion phenomena with horizontal size scale of 0.1 ft to 10^8 ft. Values of A_L range from approximately 0.01 to 0.00001.[29]

25. Table A-7 presents the computer output for several runs with varying dissipation parameters A_L. The output data most affected by changes in A_L are those related to the diffusion stage of the program, and so only output related to solids deposits is given in Table A-7. Little variability was found between the lower two A_L values and only about a 10-percent greater spreading with a high A_L value of 0.01. Although horizontal diffusion in a borrow pit water column will have some effect in the deposition of solids, it appears that only in very high energy areas will the effect be significant. This result appears reasonable since the time interval between dumping and disposition on the bottom is perhaps only 30 min to 1 hr. For turbulent diffusion

processes to significantly disperse solids, a longer time span is probably necessary.

Vertical diffusion coefficient

26. Vertical diffusion coefficients in the ocean are generally much lower than horizontal diffusion coefficients. As an example from data given by Koh and Chang [29] for a characteristic length of 100 ft, the horizontal diffusion coefficient would be about 1 ft^2/sec. For comparison, although no universal law describing vertical diffusion coefficients has been formulated, a typical value might be in the range of 0.05 ft^2/sec. As has just been discussed, computer runs indicate that variations in the horizontal diffusion coefficient have little effect on dispersion of instantaneous dumps. Vertical diffusion coefficients being perhaps two orders of magnitude lower will probably have a negligible effect on dispersion in the model. To produce computer runs for investigation of other variables, a constant value of 0.05 ft^2/sec was selected for the vertical diffusion coefficient.

Ambient velocity profile

27. Clearly, one of the important factors in transport of dredged material from instantaneous dumps is the ambient velocity profile. However, the Koh-Chang model, as presently constituted, is incapable of accommodating a horizontal velocity of any realistic magnitude. For purposes of running the program, a zero ambient velocity was selected. When non-zero velocities were attempted, the cloud very rapidly grew to enormous dimensions. The problem is that the model was not designed for dump situations in which the waste cloud becomes flattened on the bottom. The model uses the cloud surface area for entrainment calculations and an entraining velocity equal to the net velocity vector of the cloud relative to the ambient. In this case, when the cloud has flattened on the bottom, the only significant velocity of the cloud with respect to the ambient is the horizontal velocity due to ambient current since the cloud has stopped in the vertical direction shortly after entering the collapse phase. At the same time the

cloud has rapidly flattened to a pancake shape with a large horizontal diameter and little height. Thus the surface area of the cloud becomes very large compared to its volume while the net velocity used in calculating entrainment is largely parallel to the cloud surface. Because the entrainment velocity is not perpendicular to this large surface area, the amount of entrainment is considerably overestimated.

28. Another problem encountered in operating the model with an ambient current is that conservation of momentum does not appear to be satisfied. This is illustrated by running the model with an ambient current in, say, the x-direction and releasing into it, a dump having an initial velocity also in the x-direction and at the same magnitude as the current velocity. Under these conditions the dump should move downstream with the current at constant velocity (the current velocity) while it sinks. In fact, in such a run the dump decelerated and did not keep up with the current. The problem was tentatively traced to an inconsistent accounting of the momentum of the cloud and of its added mass.

29. In spite of the problems with the model some estimates can be made concerning the importance of ambient water velocity in dredged material dispersion. First, it is apparent that for instantaneous dumps that sink directly to the bottom only the near-bottom water velocity is significant. The convective descent phase occurs so rapidly (within about 4 sec in 50 ft of water) that horizontal displacement of the centroid of the cloud is insignificant. Similarly, dynamic collapse will be complete within about one and one-half minutes so that again displacement is insignificant. However, during the diffusion stage horizontal transport by an ambient current may be very important. For example, in a 1 ft/sec current, a particle initially 1 ft from the

bottom with a settling velocity of 0.005 ft/sec (silty sand) will be transported 200 ft before touching the bottom. Clay particles, if flocculation is ignored, would travel far greater distances. Unfortunately, the present state of knowledge concerning flocculation effects of silt and clay does not enable development of quantitative estimates such as would be needed for inputs to the Koh-Chang model. Estimates based on individual particle settling velocities must be made with some allowance for flocculation effects.

30. Little is known about the formation of a turbidity cloud during the dumping, convective descent, and dynamic collapse phase. However, should any material be spun off during these phases, forming a turbidity cloud, horizontal velocity would also transport this material significant distances if its settling velocity were low.

Hydrodynamic Parameters

Cloud drag coefficient

31. A number of hydrodynamic parameters related to drag forces and other similar effects are required to run the model. In general, the factors in this category are properties of the cloud and water column and are not controllable by any practical changes in dumping procedures. One such parameter is the cloud drag coefficient C_D, which is used in the calculation of the drag force on the cloud during convective descent. For solid objects moving through water, C_D is a function of the Reynolds Number. For a Reynolds Number greater than 10^3 the drag coefficient for a hemisphere convex to the flow is 0.34.[50] The value selected by Koh and Chang for their computer runs was 0.50. The total range for solid bodies of various geometries is about 0.1 to 2.0. Comparison of flow around solid bodies to that of a fluid sinking within another fluid raises doubts about a proper value for C_D. Therefore, several values were run through the program. The result, as indicated in Table A-8, is that greater drag coefficients

Table A-8

Variations in Convective Descent Drag Coefficient

C_D	Convective Descent Velocity, ft/sec		Percent Deposited in 25 min	Bottom Deposit ft	
	Max.	Impact		σ	h
0.20	13.8	13.6	77.3	139	0.14
0.35	13.4	13.2	77.3	137.5	0.14
*0.50	13.1	12.7	77.4	136.5	0.14
0.65	12.8	12.3	77.4	135	0.15

*Standard Value

produce lower convective descent velocities and less spread of the deposit, but the changes in predicted effects are very minor.

Entrainment coefficient

32. One of the major unknown values in running the Koh-Chang model is the magnitude of the entrainment coefficient. Entrainment is a linear relationship determined by the face area of the cloud, the relative velocity of the cloud face to the ambient water, and the entrainment coefficient. The entrainment rate is important because it determines the rate of growth of the cloud and thus affects the drag forces and the area of spread on the bottom. Koh and Chang have run small-scale experiments to study entrainment.[29] With various muds, sewage sludges, and dredged material and salt water, the entrainment coefficient varied over a range of 0.16 to 0.45. Differences were found when comparing a uniform ambient density to a stratified ambient density, with the uniform density producing somewhat higher results with greater variability. These experiments were carried out in a small tank only 7 in. wide, 15 in. deep, and 40 in. long, so the relationship of these data to large-scale ocean dumping may be somewhat in doubt.

33. The effect on computer output of varying the entrainment coefficient over a range of 0.15 to 0.35 is shown in Table A-9. While the range of predicted output is not extreme, more variability is seen than for any other parameter except solids settling rate. Additional research should be conducted to determine what factors influence the entrainment coefficient and how estimates of its magnitude can be made for a given dump site. Koh and Chang state that from dimensional analysis, it can be shown that the entrainment rate depends on buoyancy and vorticity, but no specific correlation was found in their experiments. Further studies, particularly in larger scale tanks or in the ocean, are warrented.

Added mass coefficient

34. As a body moves through a liquid, a certain mass of the liquid will adhere to the body and behave in some respects as if it were part

Table A-9

Variations in Entrainment Coefficient

Entrainment Coefficient	Convective Descent Velocity, ft/sec		Percent Deposited in 25 min	Bottom Deposit, ft	
	Max.	Impact		σ	h
1.0	15.4	14.8	77.2	142	0.13
*1.5	13.1	12.7	77.4	136.5	0.14
2.0	11.6	11.3	77.4	132	0.15

*Standard Value

Table A-10

Variations in Added Mass Coefficient

Added Mass Coefficient	Convective Descent Velocity, ft/sec		Percent Deposited in 25 min	Bottom Deposit, ft	
	Max.	Impact		σ	h
0.15	16.0	16.0	73.3	120	0.19
*0.25	13.1	12.7	77.4	136.5	0.14
0.35	11.3	10.4	80.0	153	0.11

*Standard Value

of the body. The magnitude of this added mass is determined by the size, volume, shape, and mode of motion of the body and the density of the surrounding liquid. Calculations involving added mass are of particular importance to ship designers, who have developed tables for a large number of geometrical shapes in various modes of motion.[50]

35. Koh and Chang, in selecting a value for the added mass coefficient C_M, considered that the range of possibilities would be 1.0 to 1.50. In their terminology a C_M value of 1.0 indicates no added mass. Tables presented for ship design in Reference 50 do not include a value for a hemisphere; for a sphere, C_M would be 1.5, and for prolate ellipsoids with major to minor axis ratios between 1.0 (a sphere) and about 10, the corresponding C_M values would range from 1.5 to 2.0.[50] Difficulties arise in selecting a proper value for the added mass coefficient because these shapes are not hemispheres and because the decending cloud is not a solid body. However, it appears that a good estimate for C_M would be in the range of 1.5 to 2.0.

36. Table A-10 shows the predicted model output for a range of C_M values between 1.0 and 2.0. Although some differences are seen, the effects are relatively minor. In running the model a value for C_M of 1.5 is suggested rather than the 1.0 used by Koh and Chang.

Bottom friction coefficient

37. The Koh-Chang model does not allow a detailed description of the ocean bottom, although it is clear that bottom topography may, in certain cases, have a significant effect on the spread of the dredged material cloud. Among the factors that would affect spreading are bottom slope, presence of channels or cuts that could trap the spreading cloud, the walls of the borrow pit itself, and the general roughness of the bottom.

38. Of these geometric factors, the only one accounted for in the model is a consideration of bottom roughness. To determine if bottom roughness is an important factor in the model prediction, four values representing a wide range of roughness were run. The results

shown in Table A-11 indicate that little difference will occur over this range of values.

Other parameters

39. A total of ten other hydrodynamic parameters that were not varied must be specified to run the program. In each case the effect of variations in these parameters was considered to be small when compared to those parameters that were varied. The values used in running the program were those from Koh and Chang.[20]

Summary

40. Operation of the Koh-Chang computer model for dispersion resulting from the instantaneous dumping of dredged material requires the input of a large number of parameters to satisfy the mathematical expressions describing the dispersion processes. Several of these parameters have been varied one at a time over a range of values considered reasonable for borrow pit dumping to establish how sensitive model output is to variation in input. The most sensitive parameter was found to be particle settling velocity. Settling velocity is also one of the most difficult factors to assess due to the effects of hindered settling and flocculation. Additional research should be conducted to study the effects of particle size, particle type, flocculation, and hindered settling in mud flows both for use with the Koh-Chang model and for other applications related to dredged material disposal in the ocean environment.

41. The only other model parameter found to be sensitive was the entrainment coefficient. Koh and Chang have performed small-scale tank studies to determine values for the entrainment coefficient, but larger scale studies in bigger tanks or in the ocean should be conducted.

42. The model was unable to accommodate adequately ambient water velocities other than a quiescent condition. This is considered to be a very serious shortcoming which greatly limits applications of

TABLE A-11

Variations in Friction Coefficient Between the Cloud and the Ocean Bottom

Friction Coefficient	Bottom Deposit ft	
	σ	h
0.001	140	0.14
0.005	138	0.14
*0.01	136.5	0.14
0.02	133	0.15

*Standard Value

the model to actual field conditions. Further model developmental work is warranted to resolve this problem.

43. In general, the Koh-Chang model was found to be relatively insensitive to variations in the input parameters. This suggests that a simplified version of the model directed specifically at dredged material dumping in the shallow ocean environment may be desirable. By attempting to eliminate those complexities that do not seriously affect model results, it may be possible both to more adequately consider the problem of an ambient water velocity and at the same time to produce a model that is easier and less expensive to use.

APPENDIX B: NAVIGATION SYSTEMS

Introduction

1. The purpose of this investigation was to assess the feasibility of dumping (and covering) dredged material deposited in subaqueous borrow pits. Since part of the problem involves navigating a vessel to a location above the borrow pit, this appendix provides a review of systems that could be used for that purpose.

2. Surface navigation normally is achieved through measurement of the vessel's position relative to other objects whose positions are known accurately. These may be fixed objects (ground stations) or moving objects (satellites, celestial bodies). Measurement normally consists of recording angles, ranges, time differences, or combinations of these. Systems that can be used to provide this information include:

- satellite navigation systems
- electronic position systems
- acoustic systems
- optical systems (surface buoys)

(Satellite systems could be considered under the electronic position systems but are presented here as a separate category.)

3. The navigational position obtained using these systems is presented in terms of repeatability or accuracy. Many systems provide a fix that is highly repeatable but accurate only if it is known relative to a standard or true value. If the position of the vessel is measured with great precision relative to two shore stations whose location is known, the fix may be accurate. However, if the location of the shore stations is not known, the fix may be highly repeatable and precisely measured, but an exact location cannot be established. There are many cases in which high repeatability is the primary requirement (i.e., returning to the same fishing location) and accuracy is of secondary importance. In most

cases, a highly repeatable system can be converted to a highly accurate system by survey methods.

4. Finally, since the accuracy of a fix is statistical it can usually be improved by taking several measurements at the same point and combining them. This may be difficult in cases where the vessel is moving and the required accuracy is very high. Where possible, both repeatability and accuracy are specified in the following sections.

Satellite Navigation Systems

5. Satellite navigation is available via the Navy Navigation Satellite System (NNSS) which uses the TRANSIT satellites. The system, with a claimed accuracy of 300 ft, was developed for the Navy by the Applied Physics Laboratory of Johns Hopkins University and became optional in 1964. Three years later it was declassified and released for commercial use.

6. NNSS is a worldwide, all-weather system from which accurate position fixes have been obtained using the data from five orbiting satellites that are supported by four tracking stations, two injection stations, the U.S. Naval Observatory, and a computing center.[51*] The satellites are in polar orbits at an altitude of approximately 600 nautical miles. Satellites orbit the earth in approximately 107 min. High-quality fixes are realistically obtained about 12 times per day using the system. Doppler shift plus satellite orbit parameters and an estimate of the user's position-time history during the pass can be used to compute a position fix.

7. Several improvements have been made to the basic NNSS system to improve its accuracy. The first of these, called translocation positioning, involved a technique by which two satellite receivers were used at separate sites to quickly establish one site position when the other site position is well known. Since the sites were reasonably close (within 500 miles), the satellite propagation errors and position errors were assumed to be the same for both

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*References are given in the References section following the main test.

sites, and improved accuracy was obtained using this method in predicting the location of the unknown site.

8. Later an even more accurate technique, called short Doppler Counting, was developed. Short Doppler Counting, which eliminated the need for the second station, involved changing the sampling period of the received signal from 2-min intervals to 4.6-sec intervals. Another improvement has been the use of a mathematical model of the earth's atmosphere to compensate for refraction of the satellite signal in the troposphere below about 10 miles altitude. Other improvements have also been made in the original system and the way in which it is used.

9. Users of the NNSS system claim accuracies ranging from 100 to 600 ft. Magnavox reported a 128-ft RMS accuracy on a single satellite pass for a stationary receiver or for a vessel whose exact velocity was known.[52] This accuracy was observed over a sample of 608 satellite passes. However, to achieve these high accuracies, the receiver must be stationary or the velocity accurately measured. Error analyses have shown that conventional methods yield a positioning error of approximately 400 m/knot of error in applied velocity. Thus, an additional error of about 1300 ft can be introduced if there is an uncertainty of 1 knot in the measured speed of the receiver.

10. The inherent high positional accuracy of satellite navigation systems can only be realized on offshore applications using integrated navigation systems that include Doppler sonar, gyro compass, and a digital computer to process and correct the data from the satellite receiver. A typical integrated satellite navigation system consists of a satellite receiver, a 4-beam Doppler sonar, a gyro compass, and a digital computer.[53]

11 The navigational accuracy of the system depends on the characteristics and operating environment of the three basic sensors: gyro compass, Doppler sonar, and satellite navigation set. Gyro compass errors are caused by misalignment with the velocity sensor (errors in latitude compensation, velocity north compensation, and velocity east compensation) acceleration induced oscillation, and gyro compass

failure. Realizable accuracy with a gyro compass is in the order of 0.2 to 0.3 deg, with a 0.1-deg error corresponding to 10.6 ft of cross-track drift per nautical mile traveled. Doppler sonar performance is dependent on water depth; speed of sound measurement; trim, list, pitch, and roll; aeration; system calibration; and equipment failure. Realizable Doppler sonar accuracy is about 0.2 percent for waters of several hundred feet depth or less. At a speed of 1 knot, the velocity measurement would contain about 0.002 knot error; since velocity error in the platform introduces a 400 m/knot error in the satellite system measure ment, this would correspond to an error of about 0.8 in the estimated position of the dump barge.

12. Magnavox has tested the accuracy of austere and complete integrated satellite navigation systems.[53] Their findings are summarized as follows:

	Satellite fix error, ft	
	Complete System	Austere System
Short Doppler	195-224	214-407
2-min Doppler	324-343	337-379

Thus, in terms of the needs of the hopper dredges and bottom dumping scows, an accuracy of several hundred feet is realizable. However, this requires an integrated system; otherwise an additional error of about 1300 ft/knot of operating speed is introduced. Since virtually none of the tugs that are used to navigate to the existing dump sites have satellite receivers, Doppler sonars, or digital computers on board, selection of this type navigation system would involve major changes, at a substantial cost, in the equipment on existing vessels. In addition, a navigation officer and electronic technician would be required to be on board to make the measurements and keep the equipment operating. The situation is similar on hopper dredges except that they do have Doppler sonar.

Electronic Positioning Systems

General

13. Electronic positioning systems exist for almost any range or accuracy desired. However, the range and accuracy capabilities tend to vary inversely. High accurate systems tend to have a short-range capability and long-range systems tend to have relatively poor accuracy. In the case of borrow pit dumping, short- and medium-range systems would be needed, and for these systems the nominal achievable accuracy varies considerably.

14. The navigation systems of interest can be broadly categorized into three groups, depending on their accuracy, as shown in Table B-1. Group 1 includes those systems with accuracies of about $\pm$1-2 miles. Group 2 has accuracies of about $\pm$100-600 ft, and Group 3 has accuracies of about $\pm$3-100 ft. A 4th group, with accuracies of about 1 ft or better, could be tabulated; however, these high-precision systems are generally not applicable to the borrow pit program.

a. Group 1 systems are typically used to meet the general navigation requirements of the U.S. Navy, the commercial fishing fleet, and other vessels that only require coarse positional information.

b. Group 2 systems are used for precise navigation typified by offshore seismic surveys, bottom mapping, and transiting through highly congested areas.

c. Group 3 systems are used for highly precise surveying, such as predredging surveys, and applications requiring that the same spot be returned to (high repeatability).

15. A recent innovation is the use of integrated navigation systems. Broadly defined, this refers to the use of other navigation and electronic equipment to enhance the capability of a basic navigation system. A typical integrated system might consist of a basic satellite system supplemented with a Doppler sonar, a gyro compass, and a digital computer, all used to measure and correct for effects such as platform motion (velocity), heading error, and atmospheric effects. An example would be where a coarse navigation system is used to cross the ocean and then an accurate system used for transiting through high-density shelf areas; in this case the integrated system might

Table B-1

Electromagnetic Navigation Systems

Estimated Accuracy ± ft	System	Approximate Range Nautical Miles	Comments
Group 1			
6000	Loran A	600	Being phased out
6000	Omega	Worldwide	Low operating costs; land identification problems; diurnal shifts
6000	Standard Decca	250	Easy to use; insufficient coverage; subject to skywave interference
Group 2			
600	Basic Satellite	200	Negligible skywave error; requires correction for ship's speed
50 - 1500	Loran C	1200	Accurate; easy to use; insufficient coverage and charts
25 - 200	Decca Two-Range	175	Circular plot-single user; error increases with range; high degree of pattern ambiguity
130 - 300	Integrated Satellite System	Worldwide	Only available every 110 minutes; requires gyro compass and digital computer; atmospheric corrections, etc., must be made

Table B-1 (cont.)

Estimated Accuracy $\pm$ ft	System	Approximate Range Nautical Miles	Comments
15 - 250	Electronic Position Indicator(EPI)	250	Error depends on distance and angle; requires ship and 2 shore stations; neglible error of intersecting angles between 30° - 150°
100 - 250	Shoran	25 - 75	Weather can reduce range; operating frequency unacceptable
25 - 150	LORAC	135	Requires 3 shore stations; continuous tracking; multi-user capability; need lane identification
10 - 150	Raydist "DR-S" & "T"	150	DR-S has circular geometry and only small geometric dilution, but suffers from range-lane ambiguity; T does not require transmitter on platform
		Group 3	
80	Precision Radar Unit	Line of sight (maximum)	Short range; operates in microwave band; complements ship's standard radar
10	Motorola Mini-Ranger	Line of sight	5 gHz frequency range
10	Decca Trisponder	Line of sight	9.5 gHz frequency range
5	Plessy Tellurometer	Line of sight	3 gHz frequency range
3	Cubic Autotape	Line of sight	3 gHz frequency range

include Omega for coarse navigation, Raydist for precise navigation, and Loran C to resolve the lane ambiguity problem.

16. Table B-1 lists several systems that can be used for borrow pit dumping navigation, depending on the desired accuracy. These include all of the readily available systems that will provide an accuracy of several hundred feet and a range to approximately 110 miles. With the exception of Loran C, enough of these systems are available that could be used immediately for borrow pit dumping. In every case, however, the system would have to be installed on shore in an area adjacent to the borrow pit of interest. Installation is not difficult, and systems are available on a rental basis. Loran C is a unique case and is covered in the following discussion.

Loran C/Loran D Considerations

17. On July 15, 1974, the Department of Transportation published an Annex to the National Plan for Navigation (NPN).[54] The purpose of the annex was stated in the following excerpt:

> This Notice modifies the Department of Transportation National Plan for Navigation (NPN) by announcing the designation and implementation of Loran C as the government provided radio navigation system for the U.S. coastal/confluence zone and the subsequent deactivation of the Loran A radio navigation system. It is issued in advance of a new edition of the NPN to provide users and other interested parties maximum lead time to plan for use of the new system.

18. The coastal/confluence zone was redefined as follows: the inner boundary is the harbor entrance, and the outer boundary is 50 nautical miles offshore or the edge of the continental shelf (100 fathom curve), whichever is greater. System accuracy required is: 2σ (two standard deviation) accuracy, 95 percent reliability of 1/4 mile on the fringes and $\pm$ 50 ft in the good coverage area, using the same receiver.

19. Loran is the acronym for LOng RAnge Navigation, a family of radio position-fixing systems that determine location by measuring

the difference in arrival of pulse signals from a number of fixed transmitters.

20. Loran A is now used extensively by fishing vessels, dredges, and tug boats operating on the continental shelf. The planned termination dates for Loran A stations are as follows:

Aleutian Islands	July 1, 1979
Gulf of Alaska	July 1, 1979
Hawaiian Islands	July 1, 1979
West Coast	July 1, 1979
Caribbean	July 1, 1980
East Coast	July 1, 1980
Gulf of Mexico	July 1, 1980

21. Loran C is a relatively new addition to the Loran family. It operates at a frequency of 100 kHz with a ground wave coverage of approximately 1000 miles over land and 1500 miles over water.

22. The existing Loran C system will be upgraded and expanded to provide coverage for the entire U.S. coastal/confluence zone and for the Great Lakes. The current system coverage is given in the Loran C Coverage Diagram, Defense Mapping Agency Hydrographic Center Chart N. O. 5130. The following dates are planned for Loran C chain operational certification to provide coverage for U.S. contiguous waters:

West Coast	January 1, 1977
Gulf of Alaska expansion	January 1, 1977
East Coast reconfiguration	July 1, 1978
Gulf of Mexico expansion	July 1, 1978
Great Lakes expansion	February 1, 1980

23. The Hawaiian Island Chain is under study to determine if the existing Loran C coverage can be improved in the area of the major islands. In order to allow a reasonable time for orderly phaseout of existing equipment, the May 16, 1974, announcement in the Federal Register provides for about 5-yr notice before the decommissioning of any U. S. operated Loran A chain that has been providing navigational services primarily for civil use, i.e., U. S. coastal/confluence zone. Included in the 5-yr period for any area will be the simultaneous operation of the Loran A and Loran C systems

for at least twenty-four months after the latter has been certified by the Coast Guard for operational use.

24. The Coast Guard claims the following advantages for Loran C over Loran A: (1) far greater accuracy, (2) around-the-clock dependability, (3) longer ranges, (4) good signals even when transmitted over intervening land, and (5) the recent availability of lower-priced, high-accuracy receivers.

25. A Loran C net is comprised of a master and two or more slave stations. The master station transmits groups of pulses at a specified group repetition period (GRP), which is common to all stations in a particular net. Since all Loran C stations transmit on a frequency of 100 kHz, the nets are identified by their respective GRP's. The repetition period, as well as the station frequency, is controlled by a very stable Cesium Frequency Standard. These master station signals are received by the slave stations, as well as by the user's mobile receiver.

26. At the slave stations, the received master station pulses are used to synchronize other independently generated pulses transmitted by the slave station. Each slave station is also controlled by a Cesium Frequency Standard. The published synchronization tolerances for the Loran C chains are generally ± 0.2 μsec or better in specified instances (1 μsec = 983 ft in range mode). This means that the slave stations are maintained within 0.2 μsec of the master station. In actual practice, the slave stations are kept within one-half of the published tolerance. Signal processing at the slave station is such as to give the effect that the master station pulses are received and retransmitted by the slave stations.

27. At the user's mobile station, a specially designed receiver tracks the three signals and determines the time differences between the receipt of the master station pulse and corresponding pulses from each of the slave stations. The time differences define hyperbolic lines of position, the intersection of which determines the position of the mobile receiver. This is called the hyperbolic mode.

28. In the range-range mode (rho-rho), the times at which signals from two stations are transmitted are known, so that if the times of arrival of the signals at the users location are measured, the distances from the two stations can be computed. These distances are the radii of circles about the respective transmitting stations, and the intersections of these circles determines the position location.

29. The accuracy and repeatability of fixes using Loran C is a subject of much discussion. The U.S. Coast Guard states requirements as: ". . . $\pm$50 ft in the good coverage area, using the same receiver." This is a repeatability requirement and the Coast Guard advises that this requires that: the receiver be in a high signal-to-noise environment; the equipment be well tuned; the equipment be calibrated at the dock (or some other fixed location); and the same operator be used. If the Loran C time differences for a given location are used by another vessel trying to find the same spot, the repeatability is about 100 ft.

30. Loran C tests conducted in the Great Lakes, by the Canadian Center for Inland Waters, resulted in an absolute accuracy (2σ) of 10 m or better at the main calibration stations.[55] Repeatability tests away from the calibration stations resulted in a standard deviation (1σ) of about 70 m.

31. Discussions with International Navigation Co. (Bedford, Mass.), a manufacturer of Loran C equipment, indicate that an absolute accuracy of $\pm$300 ft (2σ) is achievable in a new area and a repeatability of $\pm$100 ft can be achieved, using the new, lower priced receivers and a 1:3 signal-to-noise ratio. If Differential Loran C is used, a 3:1 improvement can result, and the repeatability is approximately $\pm$30 ft.

32. Differential Loran C uses a fixed location monitor receiver in the vicinity of the area to be serviced. The fixed receiver might be 80 to 100 miles from the dump site. The monitor receiver measures any deviations in the current time differences as compared to the long-term average time differences at that particular point. These deviations are caused mainly by variations in the transmission path

propagation time or in the transmitter control timing. These measured variations can then be used by the ship to correct the Loran C measured times and substantially increase the accuracy of the Loran C net. Field tests of Differential Loran C have demonstrated an improvement by a factor of 3 to 6 over conventional Loran C (for a fixed interval of 100 sec).[56]

33. Part of the difficulty in comparing accuracy and repeatability information is that tests to date have used the existing Loran C net which is incomplete. To meet the required accuracies, the Coast Guard is expanding the net so that better crossing angles are obtained for the lines of position and so that high signal-to-noise coverage exists everywhere in the coastal/confluence zone.

34. If better coverage is needed in a specific area, and this could be important for dump sites, the Coast Guard has developed "mini-stations" that can be installed to provide better crossing angles, and higher signal-to-noise ratios, in a specific area. In all the major harbor and estuary areas, they hope to provide "1/4 channel width" navigation capability. Assuming that the harbor channel is 200 ft wide, this means a 50 ft accuracy in these high-density areas. A similar installation could be provided to service a borrow pit site temporarily.

35. One of the factors in the slow acceptance of Loran C has been the high price of receivers. The Coast Guard has funded development of two low-priced receivers for Loran C. The original price of $25,000-$30,000 has now been reduced substantially. One of these is made by Raytheon (Manchester, N. H.) and the other by International Navigation Co. (Bedford, Mass.). At the present time, the INTERNAV survey receiver lists for $3600 including installation. They also manufacture more complex receivers, including one to be used as a monitor receiver for Differential Loran C. The Raytheon unit is comparable in price.

36. Loran D is a highly accurate, pulsed hyperbolic system similar to, and compatible with, Loran C. It was designed for military tactical use and the transmitter is helicopter transportable. The accuracy of Loran D is equal to, or better than, the highest accuracy attainable with Loran C. This is due to the shorter path lengths and better geometry attainable using a portable system that can be deployed to optimize a specific site accuracy. A U.S. Army Loran D transmitter system could be installed and used to provide optimum navigational capability in any borrow pit location presently envisioned on the continental shelf. This transmitter system would be fully compatible with the inexpensive Loran C receivers being marketed today, thus it would be useable by any commercial or government vessel equipped with these units.

37. Since Loran D systems are in the U.S. Army inventory, the navigation transmitter system is immediately available and could presently be installed to cover any borrow pit location currently of interest. This borrow pit could then be used by any hopper dredge, or tug-scow combination, by the simple addition of a $3600 Loran C receiver to its inventory of navigation equipment. A Loran C chart would have to be prepared for the site area as well.

Acoustic Systems

38. There are almost as many acoustic system possibilities as there are for satellite and radio frequency systems. Acoustic systems have an advantage over other approaches in that some of the systems provide a reference with respect to the borrow pit itself rather than with some distant ground station or satellite.

39. However, there are installation problems to consider as well as occasional operational problems with respect to locally generated noise (i.e., biological) and the requirement for fitting barges and vessels with below-the-waterline equipment. In addition, the acoustic

signals are degraded in shallow water due to multipath reflections from the surface and bottom interfaces.

Fathometers and echo sounders.

40. Fathometers come in a wide range of configurations depending upon the intended use. Low frequency equipment (0.1 to 1000 Hz) is used for exploration and bottom type identification. Mid-frequency equipment (5000 to 25,000 Hz) is used for general navigation to ensure that the vessel is operating in sufficiently deep water and to provide another data point in locating the vessel by comparing the actual depth to a chart depth. High-frequency systems (25,000 to 500,000 Hz) are used for precise depth determination and applications that require resolution that is greater than the capabilities of the other systems. Depending upon the water depth, both the mid- and high- frequency systems are candidates for part of the borrow pit navigation system.

41. A unique system that could also be considered is the sidescan sonar, or shadowgraph. This system uses a fan-shaped radiation pattern that is narrow in beam width along keel and the fan pattern is positioned athwartships. On each transmission, the acoustic energy that is backscattered, or reflected back to the ship, is recorded on a special recorder; as the ship moves ahead, the shape of the bottom on either side of the vessel is recorded. This system actually generates a recording that shows bottom indentations, objects lying on the bottom (or suspended above it), etc. The operator could use the sidescan to determine the vessel's position relative to the borrow pit itself, depending on how large the pit is. It is also possible to put submerged market buoys, or reflectors, on the bottom that would be highlighted on the recording as the vessel passes them.

42. Sidescan sonars have found wide application in underwater search-and-rescue systems. However, the systems available are in the high-frequency range and have operational ranges that are short relative to the borrow pit dimensions; also, the data tend to be qualitative rather than quantitative.

Acoustic Doppler

43. Acoustic Doppler systems are available but they are not effective in water deeper than a few hundred feet. These systems help to improve dead-reckoning procedures and quite often are used as part of an integrated navigation system. Simple systems require a manual plotting board. Sophisticated high-accuracy systems use gyro compasses, velocity input, and automatic track plotting equipment. At the present time their estimated useful depth is a maximum of several hundred feet of water, and their estimated accuracy is about 0.2 percent of the ship's velocity and 1 percent of the distance traveled. Most systems require that several transducers be installed below the water line on the vessel.

44. Acoustic Doppler, when used in conjunction with a radar fix on a lightship, could marginally meet the accuracy requirements for borrow pit dumping if a large pit were used and the distance from pit to lightship was short. The authors of this report do not recommend this as a borrow pit navigation system.

Transponder

45. One of the most popular methods of tracking underwater objects, or positioning a ship relative to the ocean bottom, involves acoustic transponders and/or underwater beacons. There are many possible combinations of systems and only a few will be described.

46. Passive reflectors. The simplest beacon system uses corner reflectors, or spheres, to provide a strong acoustic return in conjunction with an active system on board the vessel. On board the ship, a steerable active transducer transmits a pulse which is reflected back to the transducer and displayed on the ship. Knowing the range and bearing, the ship can then be placed on a probability circle around the passive reflector. If the reflector location on the bottom has been charted and the vessel heading is known, the vessel can then be located with respect to the ocean floor.

47. Passive systems can use three or more reflectors for very precise localization. However, there are problems of ambiguity, and the return signal is often not of an acceptable level with regard to the system noise.

48. Active transponders. Active transponders receive the transmitted signal and generate a response that is of a much larger amplitude than the response from a passive system. In addition, the signal from each transponder can be coded differently to resolve ambiguities.

49. A system of three or four active transponders provides an excellent way to precisely locate a surface vessel with respect to the ocean bottom, once the transponder field has been accurately mapped. Another unique advantage of such a system is that the same shipboard unit that is used to provide navigational inputs can provide a permanent record of the ship's location at the moment the dump takes place and actually show the beginning and ending of the dump cycle on the same record as the navigational information.

50. Transponder systems have to be implanted, but this can be done using free-falling buoys and subsurface floats and explosive-bolt release mechanisms to recover the units after the borrow pit is filled. The technology has been used for years by oceanographers and the U. S. Navy, and off-the-shelf systems are available.

51. In some applications the system must be located with respect to the ocean bottom after it is implanted, but this can be done using optical or radio frequency (RF) systems, if desired. However, it is entirely possible to use the system, relative to the borrow pit, without ever actually surveying in the transponders. In this mode, a simple RF navigation system would be used to find the borrow pit area and then the transponder system used for precise navigation with respect to the borrow pit itself.

52. There are problems with acoustic systems due to multipath reflections in shallow waters of several hundred feet or less, background ambient noise, and refraction due to temperature and salinity

gradients. The authors of this report do not recommend transponder systems for accurate location in the shallow water where borrow pits occur.

53. Hydrophone arrays. Another acoustic approach used for sophisticated underwater tracking involves putting the active transmitter on the vessel and then mounting receiving hydrophones on the bottom. The active pulse is transmitted into the water and its travel time to a number of underwater receiving hydrophones is measured and transmitted back (via a buoy and radio frequency link) to the vessel. A computer then determines the vessel location relative to the hydrophones. These systems are in use by the U. S. Navy for tracking torpedoes, submarines, and surface ships during war games and for calibration purposes. Ranges exist in Dabob Bay (Puget Sound); Nanaimo, British Columbia; the Bahamas; and the Virgin Islands. The accuracy is excellent if the water is deep enough; however, it appears as though the expense is not warranted for the borrow pit program.

Surface Buoy Systems

54. Another possibility for borrow pit navigation involves the use of any conventional navigational method to get within a few miles of the borrow pit and then switching to a buoy system that is located relative to the bottow pit itself. A field of several buoys could be placed around the borrow pit and these buoys could be instrumented with RF or acoustical transponders or beacons, and a simple system on the vessel used to track these buoys.

55. In Long Island Sound a simple buoy with a flashing light is used to mark the dump site. In practice, the barge dumps immediately adjacent to the buoy.

56. The problems that come immediately to mind involve placement accuracy of the buoys; accuracy of the buoy relative to the bottom in areas where currents are changeable; and loss of surface buoys in bad weather prior to completing the borrow pit filling, thus requiring new buoys to be implanted and surveyed.

57. While buoys have proven to be effective in shallow dump sites, their effectiveness in bad weather is questionable. As an interim tool, however, buoys could be a satisfactory solution until Loran C becomes more available.

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

JBF Scientific Corporation.
State-of-the-art survey and evaluation of open-water dredged material placement methodology, by Edward E. Johanson, Stuart P. Bowen [and] George Henry. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Contract report D-76-3)
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Includes bibliography.

1. Borrow pits. 2. Dredged material disposal. 3. Dredged spoil disposal. 4. State-of-the-art studies. I. Johanson, Edward E. II. Bowen, Stuart P., joint author. III. Henry, George, joint author. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss., Contract report D-76-3)
TA7.W34c no.D-76-3